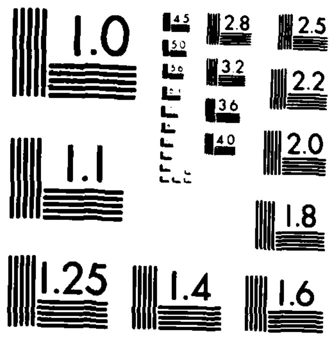
AD-A150 614 WILLAMETTE RIVER BASIN STREAMBANK STABILIZATION BY NATURAL MEANS(U) OREGON STATE UNIV CORVALLIS WATER RESOURCES RESEARCH INST P C KLINGEMAN ET AL. JUN 76 1/3

UNCLASSIFIED F/G 13/2 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

2

WILLAMETTE RIVER BASIN STREAMBANK

STABILIZATION BY NATURAL MEANS

United States Army
Corps of Engineers
...Serving the Army
...Serving the Nation

Portland District

85 02 04 093

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER / 2. GOVT ACCESSION NO. AD-A156 614	3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)* WILLAMETTE RIVER BASIN STREAMBANK STABILIZATION BY NATURAL MEANS	5. TYPE OF REPORT & PERIOD COVERED Final 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Peter C. Klingeman, PhD Jeffrey B. Bradley	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Water Resources Research Institute Oregon State University Corvallis, OR 97331	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Engineer District, Portland P.O. Box 2946 Portland, OR 97208	12. REPORT DATE June 1976 13. NUMBER OF PAGES 247
14. MONITORING AGENCY NAME & ADDRESS *(if different from Controlling Office)*	15. SECURITY CLASS. *(of this report)* Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

Bank protection
Slope protection
Channel stabilization
Bank stabilization
Stream bank protection
Bank erosion
Willamette River

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

Methods are presented that are applicable to stabilize Willamette River Basin streambanks by natural means. Feasibility and effectiveness are discussed for several techniques to alleviate or prevent bank erosion by natural means that include physical shaping of the bank, vegetative management and riparian land management. The procedures and limitations for these techniques are explained. The methods and their applicability were developed from reviewed literature, observation and investigation of field conditions, laboratory experimentation, and relative-cost comparison. The methods apply to the Willamette River and

(Cont.)

DD FORM 1473, 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

its principal tributaries, all predominantly meandering in their river behavior, where streambanks of fine-grain soils co-exist with streambed gravels and cobbles.

The techniques developed that use natural means to stabilize and protect streambanks by bank shaping include: removal of local bank irregularities, bank slope flattening and waterway widening, point bar removal, dredge spoil placement, local drainage alinement, slope flattening above low-bank revetment, and complete channel realinement. Techniques that involve vegetative management include: removal of fallen trees and debris, removal of likely-to-fall trees, planting of dense short vegetation, planting of dense bushy vegetation, replanting of scoured zones, vegetation growth control, vegetation removal from bars, planting at the foreground of cutbanks, planting of living fences, and tree buffers and deflectors at the base of the bank.

Willamette River Basin Streambank
Stabilization by Natural Means

A Report Prepared for

U.S. Department of the Army
Portland District, Corps of Engineers

by

Peter C. Klingeman, Ph.D., Principal Investigator
Jeffrey B. Bradley, Graduate Research Assistant

Water Resources Research Institute
Oregon State University
Corvallis, Oregon 97331

June 1976

ABSTRACT

Methods are presented that are applicable to stabilize Willamette River Basin streambanks by natural means. Feasibility and effectiveness are discussed for several techniques to alleviate or prevent bank erosion by natural means that include physical shaping of the bank, vegetative management and riparian land management. The procedures and limitations for these techniques are explained. The methods and their applicability were developed from reviewed literature, observation and investigation of field conditions, laboratory experimentation, and relative-cost comparison. The methods apply to the Willamette River and its principal tributaries, all predominantly meandering in their river behavior, where streambanks of fine-grain soils co-exist with streambed gravels and cobbles.

The critical problems of streambank erosion at sharp concave banks cannot be effectively met by natural stabilization techniques; instead, extensive riprap or other massive structural methods are required for adequate protection. But at many other erosion zones the flow conditions are not as severe and natural means of erosion control can be applied, singly or in combination, to effectively retard or even halt erosion. Possibilities also exist for use of natural methods in conjunction with toe revetments or other massive structural methods. The

effectiveness of erosion control varies with river circumstances and stabilization technique.

The techniques developed that use natural means to stabilize and protect streambanks by bank shaping include: removal of local bank irregularities, bank slope flattening and waterway widening, point bar removal, dredge spoil placement, local drainage alinement, slope flattening above lower-bank revetment, and complete channel realinement. Techniques that involve vegetative management include: removal of fallen trees and debris, removal of likely-to-fall trees, planting of dense short vegetation, planting of dense bushy vegetation, replanting of scoured zones, vegetation growth control, vegetation removal from bars, planting at the foreground of cutbanks, planting of living fences, and tree buffers and deflectors at the base of the bank. Techniques that involve riparian land management include: top-of-bank vegetation zone, controlled irrigation water application, provision of bank drainage, control over bank access and traffic, and hydraulic design of river-related structures.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

Streambank erosion is a major water resource problem in the United States. Such erosion results in the loss of a substantial amount of productive land each year in Oregon. Particularly significant are those losses in the heavily populated Willamette Basin along streams tributary to the Willamette River and along the banks of this 12th largest river in the United States. The riparian lands affected here include numerous urban and suburban areas as well as the extensive agricultural areas which contribute to the state's principal industry.

The Willamette River and its tributaries flow through alluvial lands on the 3500 square mile (9000 square kilometer) valley floor. The channels meander extensively. In many locations the meander belts (zones over which the channels have meandered during the past) may be 30 to 50 times as wide as the actual channels themselves.

The floodplain of the Willamette is many miles in width, owing to the flat gradients of many tributary streams as they near the trunk stream. Meandering of river channels involves the natural processes of streambank and streambed erosion, the transport of these sediments together with other sediment derived from land erosion, and sediment redeposition on the streambed, at bars, and at streambanks. The erosion of streambanks at one location is accompanied by the eventual development of new streambanks elsewhere.

Human settlements and developments along the Willamette River and its tributaries are a normal condition, following the historical pattern of cultural development elsewhere in the United States. Accessibility to the rivers for water supplies, to convey away wastes, and to provide a waterway artery for commerce have been dominant reasons. Because of the breadth of the floodplain, cultural development has led to extensive encroachment upon the floodplain and substantial capital investments there over the past century. Consequently, streambank erosion and flooding of nearby lands leads to considerable economic disruption at affected locations.

As a direct consequence of the development and use of valuable riparian and floodplain lands by man, significant efforts at streambank protection and stabilization have been carried out during the past century. The most notable and extensive program of streambank protection in the Willamette Basin is that of the Portland District, U. S. Army Corps of Engineers. But even private revetments have been constructed to protect threatened lands.

The intent of streambank stabilization efforts in the Willamette Basin, as elsewhere, has been to halt severe bank erosion at critical reaches of the river system so as to protect valuable investments that are jeopardized by the loss of land or by threat of a change of channel location. In effect, streambank stabilization efforts seek to "freeze" or make "static" a "dynamic" process of channel change that is otherwise continually taking place. This is a formidable task! Permanent

protection normally calls for massive stone revetments. Because of the costs and difficulties involved, as well as for aesthetic and ecological reasons, it has not been practical nor desirable to attempt to stabilize the entire river system.

When federal or state assistance is not available to provide needed bank protection, this situation leaves the individual riparian land owner in a dilemma. He may have made a sizeable investment in land and facilities that he wishes to protect. How, then, can he protect eroding property? What can this individual landowner do that will reduce or retard the erosion process at his land and that will hopefully be within economic reach of accomplishment?

These questions are addressed in this report by means of an investigation to develop information on what might be called "natural" means of streambank stabilization--one of several alternative approaches for achieving streambank rehabilitation and erosion protection. The natural means of bank protection examined here include physical shaping of the bank, vegetative management, and land management adjacent to the streambank. A sufficiently broad interpretation of these means of protection is given here to permit some limited structural protection in combination with natural protection if it might conceivably be accomplished within a landowner's own resources. This broad interpretation does not, however, include the use of extensive riprap or other massive structural measures.

Information developed in this study came from three sources: literature review, field observation, and laboratory experimentation. The

literature review utilized all available material on the subject from the Oregon State University Library that had been previously identified in the Literature Search on Natural Means of Streambank Stabilization completed for the Portland District, Corps of Engineers, Department of the Army, in January 1975 by Peter C. Klingeman, under Contract DACW57-75-M-1086, as well as more recent literature on the same subject. Field observations were made at several locations along the Willamette River and its tributaries. Laboratory experimentation at Oregon State University was used to gain further insights to streambank shaping and vegetative management by modeling streambank situations in a hydraulic model. The reviewed literature, field observations, and laboratory experimentation are discussed in following chapters of this report.

II. LITERATURE REVIEW: TECHNIQUES AND METHODS FOR USING NATURAL MEANS OF STREAMBANK STABILIZATION TO PREVENT EROSION OR RETARD ITS PROGRESS

COMMON TECHNIQUES FOR STREAMBANK STABILIZATION

The last few decades have seen the implementation of numerous techniques for streambank stabilization. These have focused primarily upon the concave banks along the "outsides" of curves where erosion and streambank losses are most severe. Most of the techniques applied might be called "mechanical" or "structural"; several techniques also utilize natural means of protection.

Erosion protection and control methods can be classed in broad terms as permeable or impermeable, flexible or rigid, and temporary or permanent. Their general purposes are: (a) to produce a protective bank layer that resists the forces of flowing water; (b) to create sufficient bank roughness to reduce the local velocity and erosive force on a streambank; (c) to divert flow away from erodible banks; and (d) to stabilize the streambed gradient and prevent its lowering with accompanying undercutting of the banks (38).

As background to natural means of protection, a brief description of the mechanical/structural category of streambank protection is helpful to show what it is intended to accomplish. This category can be further subdivided into two groups: (a) revetments designed primarily

to prevent the erosion of an existing bank, and (b) training structures designed primarily to guide the flow and/or promote controlled sediment deposition (38). The various methods also may be combined in numerous ways.

Revetments may be of the blanket, pervious, solid, groin or mattress type. Revetments are placed on banks that have been previously sloped and shaped to some desired alinement. Revetments of the blanket type consist of rock, concrete, asphalt, stone-filled gabions, or other materials. Revetments of the pervious type include open fencing, pile structures, cable-connected jacks or similar structures. These not only protect existing banks but also encourage sediment deposition by guiding the flow. They are used where the angle of flow attack is small. Revetments of the solid type involve fencing backed by placed materials in order to gain resistance to the flow forces. Groin-type revetments involve short spurs extending from the banks normal to the flow. Mattresses may be made of woven willows, joined concrete blocks, lumber ballasted with rocks, or other materials. They are used as continuous, flexible, articulated blankets that extend from the low water line out to the thalweg of the stream and act as highly effective accessories to bank protection above the low water line (38).

Training structures direct the flow so that banks do not receive the full strength of the current, which instead is guided so that a channel will be scoured at some distance away from the bank and so that secondary currents will bring sediment into deposition zones of reduced velocity adjacent to the bank. Pervious structures are more effective than solid

structures in this respect. Types of training structures include rock dikes, timber pile dikes, jack dikes, fence rows, cabled car bodies, dumped rubble and other material alined into dikes (38).

By the expression "natural means of streambank stabilization" it is meant that bank shaping, vegetative management along streambanks, and riparian land management are applied, separately or in combination, to achieve streambank protection. In contrast to the mechanical/structural techniques of streambank stabilization, which place heavy reliance upon construction using engineering materials, the natural means of streambank stabilization place minimum reliance upon such materials and maximum dependence upon nature, aided by man, to provide the needed protection.

Natural methods of streambank stabilization have previously been used most often in conjunction with mechanical/structural techniques. They have on occasion, however, been used effectively by themselves. The particular stream conditions found at a given site appear to determine whether separate or combined use is called for.

This literature review is organized to address in sequence each of the three natural means of bank stabilization identified above. A section is also included dealing with combined natural and structural methods of streambank protection. The type of streambank protection that may be most effective is dependent on the relative importance of various significant stream parameters. This subject is addressed in a following chapter.

BANK SHAPING

In the design of structural revetments to prevent erosion of an existing bank by means of a protective layer, emphasis is placed upon (a) the careful sloping and shaping of the bank prior to placement of the protective layer and (b) the careful alinement of the shaped bank to the oncoming streamflow (38). These design steps stem from efforts to provide as much natural assistance in erosion control as possible, in addition to that gained from the protective layer, and from efforts to assure that the protective layer will itself be protected as much as possible from erosive forces of the flowing water. Thus, the recommendations developed for structural control and the reasons behind them are also important in natural control of streambank erosion.

Bank Alinement

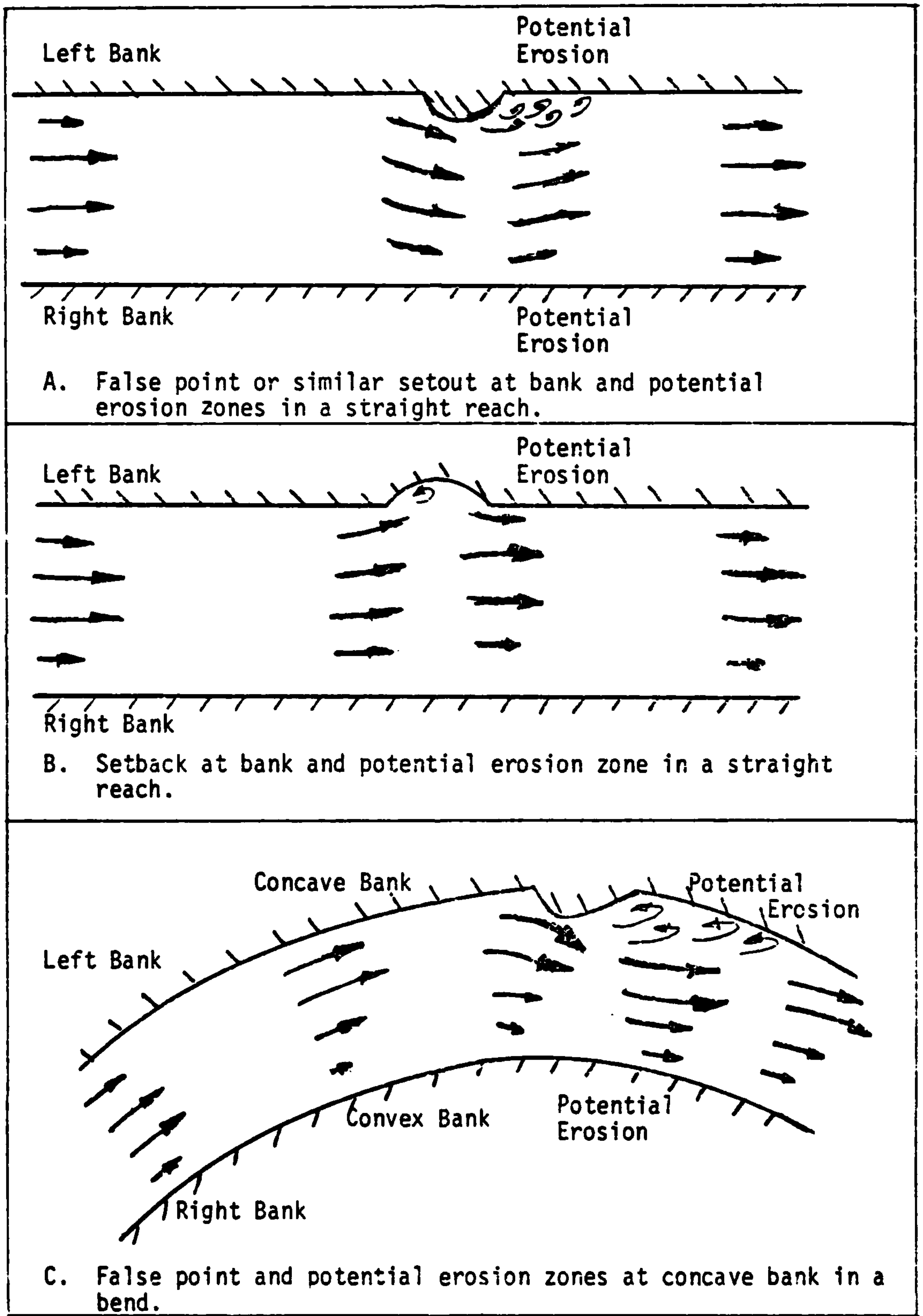
The proper alinement of the streambanks to the channel axis is of critical importance, particularly at curves where streambank erosion is most common. The alinement goal at river bends should be a smooth, gradual bend having neither too abrupt nor too flat a curvature and being free of curvature reversals within the main curve. Curves and straight reaches of a stream should be free of false points or other irregularities in the bank line (38). Such precautions are intended to keep the flow moving parallel to the banks, rather than at some sharp angle of attack or with eddies swirling against the bank downstream of bank irregularities. At curves, this parallel-flow condition cannot be met because of the secondary currents and spiraling flow associated with larger surface velocities that are carried toward the outside of the curve by centrifugal

forces, causing a counter-flow toward the inside of the curve along the streambed. Giving the bend a smooth, gradual curvature restrains the growth of these secondary currents.

Figure 1 illustrates simplified situations where bank irregularities occur and affect flow patterns and the potential for local erosion. Bend alinement situations for which the bend sharpness varies and influences the flow patterns are shown in Figure 2.

Several additional constraints should be placed on streambank shaping as an erosion control measure (38). Paramount among these, the existing meander pattern should be generally maintained, within limits, when changing the channel alinement or making cutoffs. The stream's energy dissipation balance should be maintained by preserving the overall channel slope and length even though local modifications are tolerable and may be desirable. But general straightening of a meandering stream in an effort to eliminate bank erosion should not be attempted because the balance between energy dissipation and sediment bedload transport will be severely disrupted and meandering will be reinitiated, possibly at unexpected locations.

Information is available regarding desirable dimensions for meandering channels (6, 8, 22, 23, 38). The reviewed literature generally indicates that the meander width and length are related to the bankfull streamflow and that the radius of curvature of a bend should be some multiple of channel width. There is no concensus on this multiple. A factor of 2 or 3 is cited as providing minimum flow resistance but larger



A. False point or similar setout at bank and potential erosion zones in a straight reach.

B. Setback at bank and potential erosion zone in a straight reach.

C. False point and potential erosion zones at concave bank in a bend.

Figure 1. Bank Alinement Situations Involving Bank Irregularities.

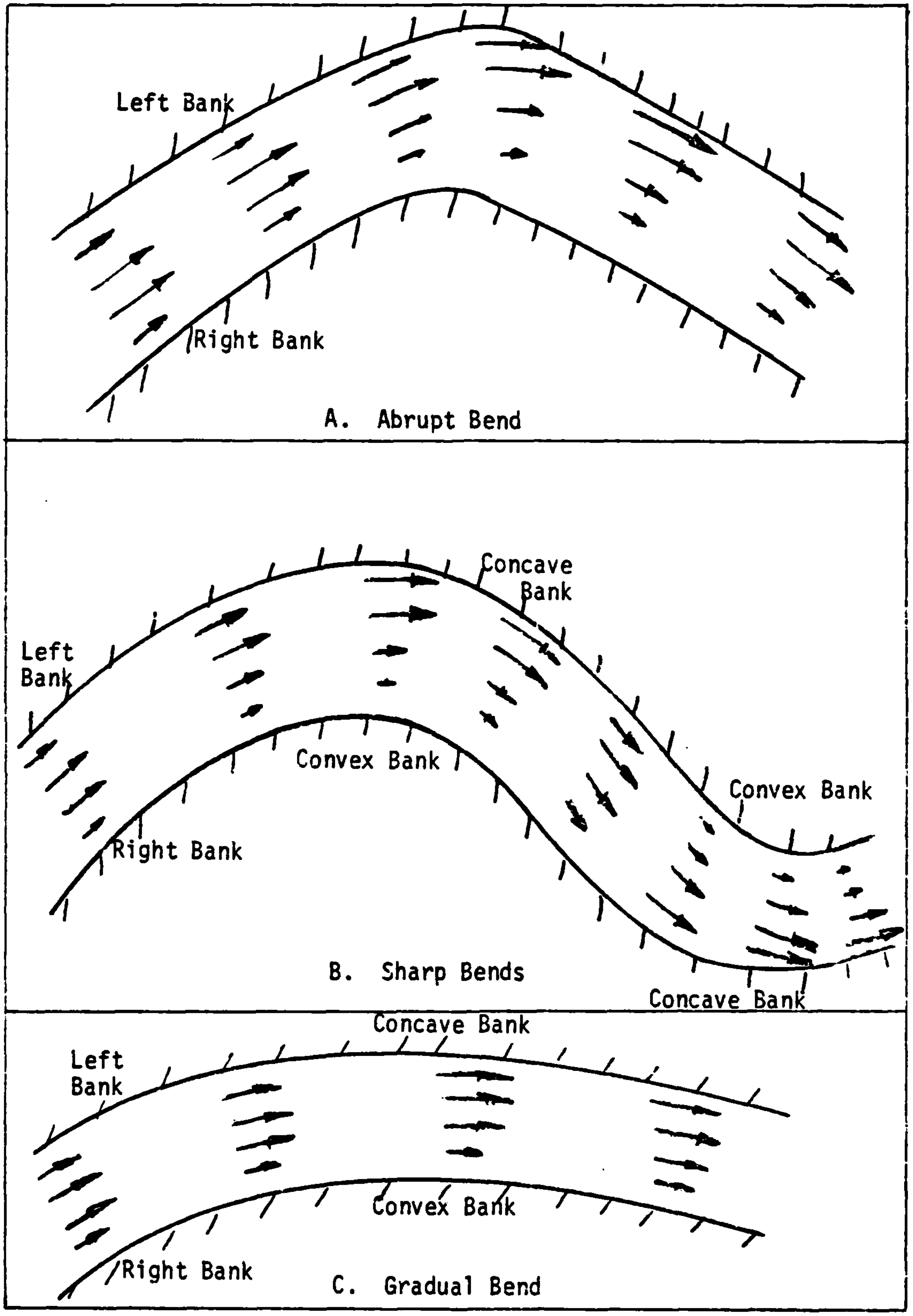


Figure 2. Bend Alinements

factors, even exceeding 10, appear to be required to reduce erosion at the concave bank.

Angle of Flow Entry to Bend

The entry angle of flow to a bend may be defined as the angle formed by a tangent to the bank line at the bend entry and the principal flow line of the stream there (38). The angle of attack of the flow against the bank can be defined in a similar manner. Normally, the flow lines considered are those at the water surface. These usually have the largest entry angle.

As the flow enters a bend, it is important that the flow not be turned too abruptly if directed against an erodible bank. Otherwise, strong secondary currents will form and carry away material from the base of the bank that would otherwise offer toe protection there. If the bank is highly resistant to erosion, the abruptness of the turn will be less critical.

The available literature (summarized in (38)) points out that the desirable entry angle to a bend should be less than 15 degrees and that good practice is to limit the angle of entry to below 25 degrees in order to hold maintenance problems on protective revetments to a minimum. At angles greater than 25 degrees, maintenance problems increase disproportionately; should the angle exceed 30 degrees the situation becomes essentially unmanageable. Also, at angles approaching 45 degrees the flow will tend to "bounce" from side to side in its channel and may create instabilities that extend downstream a considerable distance and could

affect the next several downstream bends (13). The use of spiral entrances and exits at bends has also been recommended in order to give a more gradual transition between a straight and a curved reach.

Channel Width

Stream channelization, which is largely structural in the techniques applied, places certain constraints upon proper channel width. To the extent that natural erosion control by means of bank shaping can affect the channel width, these desirable conditions for channel width should be taken into consideration. The constraints on channel width really focus upon the sediment transport process in a stream and how it may be locally altered because of changes in cross sectional shape that result from channel widening or narrowing.

Guidelines on channel width and reasons for their use (38) are summarized as follows: (a) the channel should be kept wide enough so that a local constriction is not formed which could cause excessive scour of sediment and degradation of the streambed; (b) the channel should be kept narrow enough so that a local expansion is not formed which could cause excessive deposition of sediment and aggradation of the streambed; (c) the channel should be kept narrow enough so that bar formation does not occur at low flows which could force the flow against the base of streambanks adjacent to and downstream of such bars; (d) avoidance of low-flow bars is particularly important if the stream carries a heavy debris load (logs, branches, etc.) that could become stranded on the bars at receding flood flows and amplify the adverse effects of crowding the flow against the banks; (e) variations of channel width should be avoided because of

the possibilities for high-flow local sediment deposition followed by lower-flow scour and shifting of the thalweg (main deep thread of flow) and alinement of the channel. It is further noted that for a meandering stream the critical width is that at the crossings between successive bends, where excessive sediment deposition must be avoided. Within the bends, the cross sections tend to be self-adjusting in accord with the dimensions of the meander. From this it appears that gradual bends will have larger, better controlled channel widths than will abrupt bends with intense secondary currents capable of rapid buildup of bars along the inside curve of the bend.

Bank Slopes

Proper bank sloping has been significant in resisting streambank erosion and caving caused by flowing water on rivers such as the Winooski (Vermont), Snake (Washington), Little Snake (Wyoming), Rappahannock (Virginia) and smaller streams (Great Lakes States) (1, 5, 13, 18, 29, 33). In some cases sloping was effectively used alone. In others it was used with vegetation, mattress structures, or other forms of riverbank protection to greatly enhance bank stabilization.

The type and texture of soil that the riverbank comprises appears to be the governing factor in the choice of an adequate slope. The following typical values have been suggested:

Soil Texture	Suggested Bank Slope
Heavy clay	1 1/4-to-2 horiz.: 1 vert.
Medium-textured soil	1 1/2-to-2 horiz.: 1 vert.
Sand, gravel, cobbles	2-to-4 horiz.: 1 vert.

In essence, the more granular the bank soil is, the flatter must be the shaped bank slope to provide effective resistance to erosion. In each case, the suggested bank slope provides a flatter slope than the angle of repose of the material. This assures that the material will not tumble or slide downslope due to its own weight under static or modest-flow conditions.

Avoidance of near-vertical banks keeps the main thread of flow somewhat away from the bank material and widens the distance of velocity decrease from main thread to streambank. This in turn helps reduce the shear stress against that bank. Flat slopes also enhance bank stability against sliding and caving. However, with flat slopes the toe of the slope may lie directly beneath the thalweg (more so than with a steep slope) and thus near a zone of high turbulence and shear stress.

Length of Zone Requiring Bank Shaping

When bank shaping is used in preparation for placement of a protective revetment, the normal recommendation (38) is to carry the protection from "hard-point to hard-point"--that is, upstream and downstream well beyond the critical zone to banks that are resistant to erosion. When a complete protection scheme is not justifiable, a partial stabilization can still be undertaken at the most critical zones. Similar criteria as for complete stabilization generally apply to partial stabilization. However, it must be recognized that partial stabilization does not completely solve the erosion problem, although it may significantly retard erosion.

Extending these recommendations, bank shaping for the purpose of natural streambank stabilization should also include a zone long enough

to span the bank where the flow has attacked most vigorously and should "feather out" gradually to the unshaped bank. Abrupt transitions should be avoided because of the eddies and reflected flow which might be generated there.

VEGETATIVE MANAGEMENT ALONG STREAMBANKS

Vegetative management methods along streambanks include the planting of vegetation, protection of growing vegetation, control over the type, growth and size of vegetation, vegetation removal, the use of mattresses made of brushy and woody vegetation, and the use of entire trees to act as flow deflectors along the bank. The principal function of vegetation in erosion control is to keep the fast-moving waters away from erodible soils (31). In cases where the method involves new plantings, growth management is a necessary adjunct following the initial planting. Vegetative management techniques deal principally with concave streambanks, where scour is the most common and most severe problem.

Vegetation can effectively protect streambanks in several ways (25, 39). First, the root systems help hold the soil together and increase the overall bank stability by this binding network structure. Second, the exposed vegetation (stalks, stems, branches, and foliage) can increase the roughness resistance to flow and reduce the local flow velocities, causing the flow to dissipate energy against the deforming plant away from the soil--energy that otherwise might have been used by the flow to exert greater shear stress against the streambank soil. Third, the vegetation acts as a buffer against the abrasive effect of transported materials. Fourth, close-growing vegetation can induce sediment deposition

by causing zones of small velocity at the bank where shear stresses may become small enough to allow coarse sediment to settle out of the flow.

Vegetative management can be used alone with considerable benefit, particularly on gradual curves of large streams and on small streams that are relatively compact in cross section rather than broad and shallow. These represent situations where bank roughness effects are likely to be important compared to bed roughness effects and where mature vegetation can influence the near-bank velocity (31).

Vegetation management is also beneficially used in conjunction with mechanical/structural means of protection. The role of vegetation in such cases is often to provide long-term stabilizing effects that enhance the operation of the structure and minimize its need for maintenance or repairs.

Vegetative management methods at streambanks can be subdivided on the basis of physical location into top-of-bank, face-of-bank, and adjacent-to-bank control. The first category rarely involves inundation of the vegetation; the second category involves a zone of frequent water level fluctuation and plant inundation by the stream; the third category involves accumulations of dead vegetation in the channel near the bank. Figure 3 illustrates these three zones for vegetation management.

Top-of-Bank Vegetative Management

Top-of-bank protection includes planting of vegetation within close proximity to the river. Such vegetation includes grasses and legumes (herbaceous material) as well as ground covers, shrubs and trees.

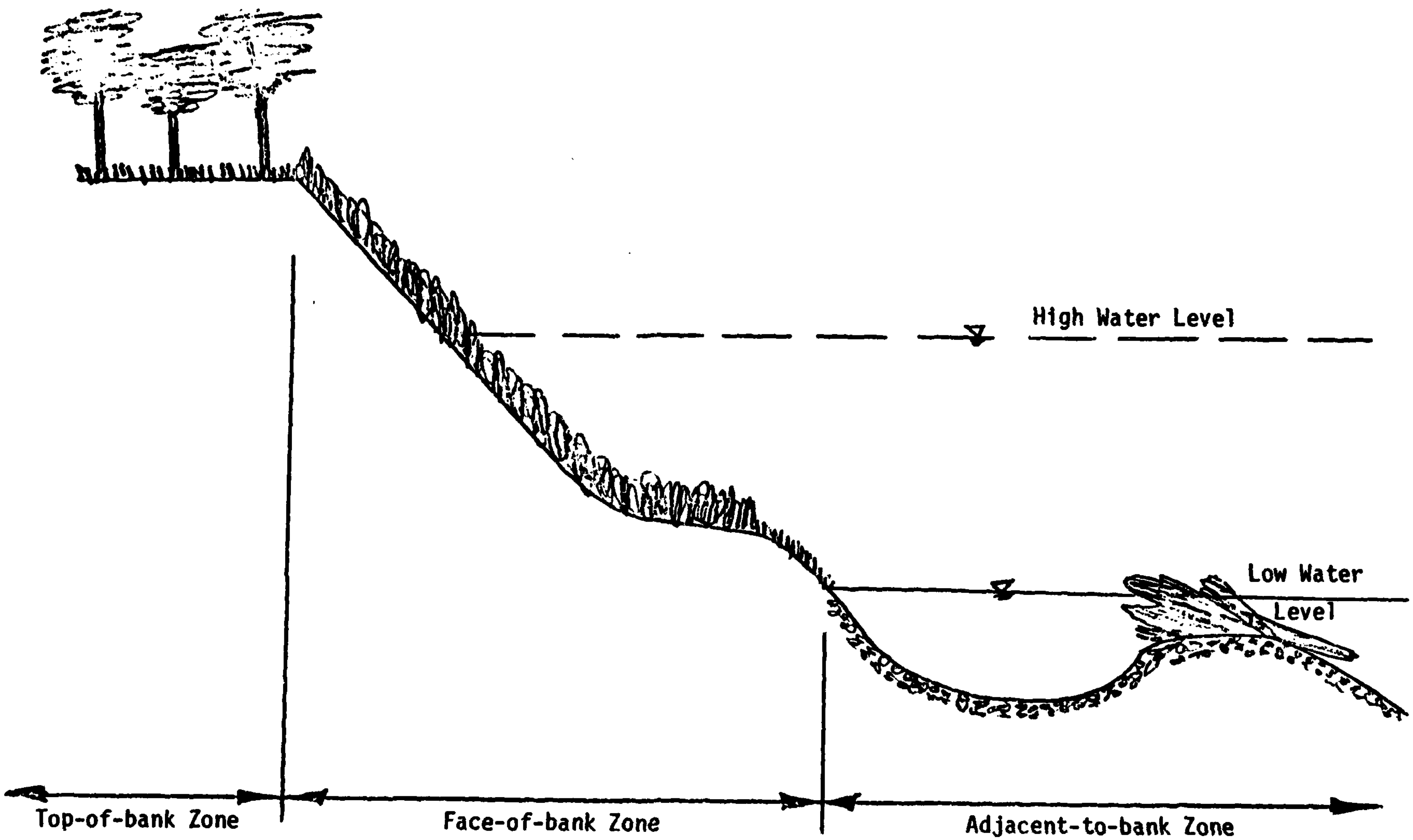


Figure 3. Vegetation Management Zones

Top-of-bank vegetation management reportedly enhances streambank protection in at least three ways. First, vegetated land slows down the surface runoff and induces infiltration of this runoff into the soil before it reaches the top edge of the bank. This prevents surface runoff from causing rivelets and gullies down the face of the streambank which could grow over time and badly damage the bank. Second, the root systems of vegetation tend to stabilize the adjacent ground and reduce its rate of erosion substantially. Third, a vegetative border keeps cultural encroachment away from the top of the bank (24).

Most forms of hardy grasses and shrubs effectively protect against bank erosion. Planted trees have thrived near riverbanks in many parts of the country (e.g., Winooski River, Vermont; small streams in Utah, Ohio and the Southeast) include several species of willow, cottonwood, black locust and water birch (1, 13, 14, 24, 32). Several willows, maples, alders, Oregon ash, black hawthorn and cottonwoods are found along the Willamette and its tributaries (43). Kudzu and honeysuckle have been effective plantings in cultivated fields near streams in the Southeast (24).

Where whole areas cannot be planted with top-of-bank vegetation, mathematical models suggest that staggered planting patterns will be more effective than rows in retarding flow rates and reducing sediment yield to the stream (25).

Face-of-Bank Vegetative Management

Face-of-bank vegetative protection deals with vegetative stabilization from the streambed up the face of the bank to the top of the bank. In many cases, the base of the bank at the streambed is not easily defined

and must be arbitrarily chosen. In other situations, the bank is relatively steep to some distance below the water line before abruptly flattening out under water and the base of the bank can be easily identified as being this break of slope. Similarly, the top of the bank is clearly marked as the change from flat land to a steep cut bank in some locations but is a poorly defined gradual change of land slope at other locations. These difficulties of definition should only slightly influence the following discussion.

Vegetation used for face-of-bank stabilization must be selected on the basis of strength, resilience and vigor, as it is periodically inundated by flood waters (24, 31). (In the Willamette Basin such inundation normally occurs during the winter dormant period of most vegetation. Thus, the vegetation must be sufficiently hardy to withstand prolonged wetting at such times.) Woody vegetation with short, dense, flexible tops and a multitude of roots is highly satisfactory. Other important considerations include rapid initial growth, ability to reproduce, and resistance to disease and insects (1).

Another consideration in the choice of vegetation is the bank slope on which the vegetation can establish growth and thrive (14, 18, 24, 26, 31). If no bank shaping is to be undertaken, the vegetation must be suitable for use on the existing bank. As an alternative, bank shaping may be used as a means of providing a bank slope suitable for growth of the desired vegetation. Vertical slopes are considered unsatisfactory unless a suitable sediment deposit or soil from bank caving is found at the base of the vertical face and is unsubmerged for a sufficient part

of the year to allow planting and growth of vegetation. Such vegetation is likely to be inundated during much of the winter. The vegetation should extend up the entire face of the bank.

The types of vegetation used for slope protection include grasses, legumes, groundcovers, shrubs, woody materials and small tree cuttings. Herbaceous material and shrubs, once securely rooted, can often develop good growth in one growing season. Woody materials and small tree cuttings, on the other hand, normally require two years of growth before they become effective as bank protection. Often, a mixture of woody and herbaceous vegetative types is desired, such that the soil surface is protected either by a very dense stand of shrubs or by shade-tolerant grass under a less-dense stand of woody growth (31).

Herbaceous plants well suited for rapid growth along streambanks around the country, most of them also suited to the Willamette Valley, include tall fescue, rye grass, crown vetch, Reed canary grass, brome grass, creeping red fescue, birdsfoot trefoil, meadow foxtail, bentgrass, and sericea lespideza (18, 31, 34, 42, 43, 44). Climate, soil type and texture, and individual characteristics of the grasses influence their suitability. Most often, combinations of the above are used, including a variety that gives quick, early protection, even if not the most desirable at maturity (31).

Suitable shrubs and brushy plants for streambank protection in Western Oregon include salal, dwarf willow, dogwoods, rose, hazel, vine maple, blackberry, poison oak, swordfern, bracken fern, snowberry and thimbleberry (43, 44).

Successful tree species planted as cuttings in such locations as the Northeast, the Southeast, Utah and Oregon include white and black willow, cottonwood, water birch, purple osier willow, red osier dogwood, and silkey cornel (1, 13, 14, 24, 32, 33, 36, 43). Willows of various species are particularly effective.

Small tree cuttings should be established in the streambank during their dormant season: winter or early spring. Planting recommendations include placing the cuttings one to two feet above the low-water line. Cuttings should be approximately five to eight feet in length, one to four inches in diameter, and should be planted in sandy soil about three to four feet deep. Recommended spacing between cuttings varies, averaging six to eight feet for small streams in Utah and the Southeast (14, 24). Tall vegetation should be planted in a random manner rather than in rows to avoid pathways for highwater channeling behind the vegetation.

Small willow logs can be used in place of tree cuttings. These should be established with their butt ends under water at a four- to six-foot spacing between logs (24).

The roots of vegetation are important (31). They must hold the vegetation against the stresses of flowing water without disturbing the soil. When partially exposed, they still retard flows near the soil and may still be able to support growth.

The effectiveness of vegetative plantings in protecting streambanks is greatest during late spring, summer, and early autumn, when foliation is greatest, and is considerably less during the dormant season due to defoliation and reduced resiliency (18, 31, 36). However, even during the dormant period the branches and stems can offer protection to the banks.

Several procedures have been used in different parts of the country to insure the growth of a planted slope (1, 3, 13, 18, 24, 31, 34, 36, 42). These are not failsafe but considerably increase the chance of survival of plantings. Such techniques include the addition of topsoil on sandy and gravelly slopes, irrigation and fertilization to stimulate growth, and mulching (usually wood chips) of the seedlings. Protective meshes or mats might be used on newly seeded banks to provide temporary slope and vegetation protection. Vegetation can grow through these mats but erosion cannot take place. The most common of such devices is the brush mat, composed of a 12- to 18-inch brush layer tied down to the bank. Brush mats commonly consist of speckled alder, red osier dogwood, willow, and gray dogwood, although most types of similar material will suffice. Other mat materials used for the same purpose include straw, straw-asphalt mixes, fiberglass, and jute. All mats of this basic type deteriorate within about two years' time.

Adjacent-to-Bank Vegetative Management

Vegetation management adjacent to the bank includes control over snags and debris in the river near a streambank. These cause local currents that are often directed against the bank. Accordingly, such obstructions should be removed (13, 14, 24). The removal of snags and debris accumulations from the channel also serves to enlarge the effective waterway and channel flow capacity by increasing the usable cross-sectional area and by reducing the boundary roughness (38).

When part of the eroding bank is subject to prolonged submergence, it is difficult to develop any vegetative material there (31). This means

that part of the bank may need to be protected by other methods. These would normally include adjacent-to-bank measures that involve structures, some of which could incorporate vegetation in significant amounts.

Vegetation Structures for Bank Protection

Types of bank protection exist which use natural vegetation, living or dead, as a substantial feature of the structure. These can be termed vegetation structures. Such erosion control structures have a limited effective life of several years duration. Several such devices have proven effective in fighting bank erosion and will be described here.

Willow fascine mattresses, placed perpendicular to the riverbank, are used on even major rivers like the Mississippi (15). Lightly bound willow bundles are cabled and wired into a continuous mattress which is then ballasted with rock. Such structures are quite heavy and must be first built above the bank that is to be protected. Normally, they are laid in an upstream-to-downstream direction.

Lumber mattresses "woven" into a square weave and weighted with stone are sometimes used (e.g., the Savannah River in Georgia) (15, 40).

Whole tree deflectors have been established at the submerged toes of banks on rivers like the Winooski (Vermont), small Utah streams, small Southeastern streams and even on larger streams (13, 14, 15, 24, 36). They may be rigidly positioned or tied to a flexible boom. For installations on the Winooski River they have been used in water approximately 14 feet deep. Good results were obtained on small Utah streams when deflectors projected downstream about 30 degrees. The butt ends, placed

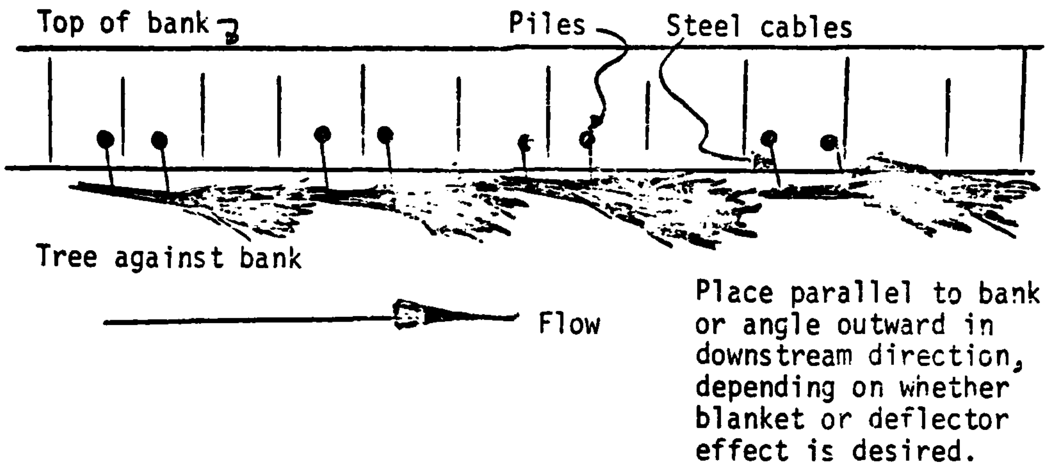
upstream, are anchored to the bank by cables and deadmen. Structures of these varieties have an average life span of five to seven years. Deflectors are often supplemented by brush mats and vegetative plantings.

Blankets consisting of large trees have given effective protection on the Winooski (Vermont) and on small streams near the Great Lakes, in Utah and in Southern California. The trees can be cabled end-to-end with the top of one tree cabled to the bottom of the next, and then alined along the bank. The whole system is anchored to deadmen placed in the bank. Suggested tree diameters vary from 20 to 24 inches. Elms, willows, and other hardwoods have been used for this purpose. As with whole tree deflectors, the life of this system is about five to seven years.

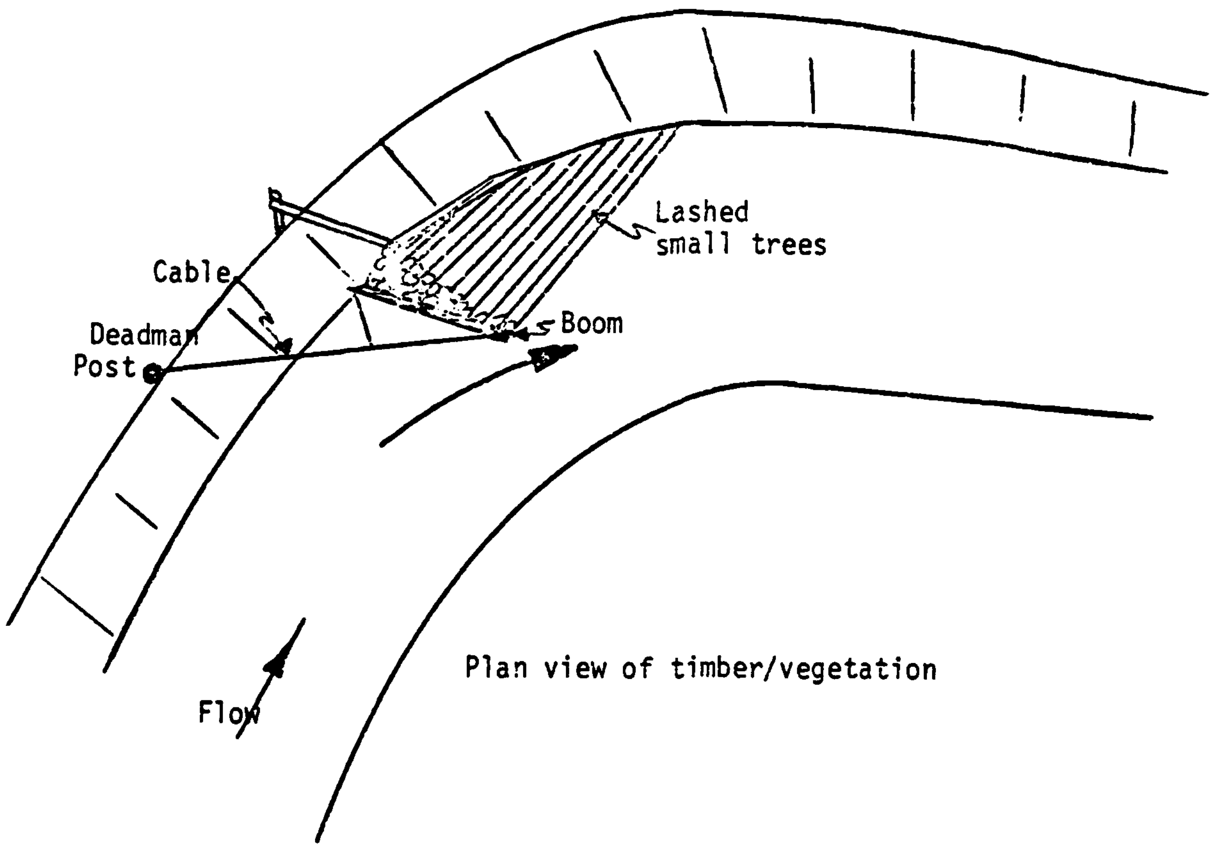
Vegetative types of timber jetties consist of articulated masses of small trees lashed to a boom. They extend out into the river and the boom is anchored to the bank by cables and deadmen. Such structures are temporary and induce sediment deposition downstream of the booms. When sufficient sedimentation has taken place, vegetation can be planted and allowed to gain a foothold, as on the Savannah River (Georgia)(7, 15, 24, 40).

Figure 4 depicts the use of whole-tree deflectors and blankets as well as vegetative timber jetties to protect steeply eroded banks.

The above methods have important limitations (15). Whole tree deflectors experience a decreased efficiency with increasing current velocity. Wood and willow fascine mattresses should be used solely as underwater protection, as they rot when exposed to air.



Plan view of whole tree deflectors and blankets



Plan view of timber/vegetation

Figure 4. Vegetation Structures Incorporating Trees in Bank Protection

Importance of Maintenance

No vegetative management scheme can serve its purpose well unless a good program of regular maintenance is undertaken following the initial plantings (18, 24). Otherwise, future local failures of the vegetative protection can lead to renewed erosion.

Replanting is often a necessity. As plants are washed out or die, erosion in that local area may occur. Trees which rot away in tree deflectors or mats should be replaced (13, 14, 24).

Vegetation management involves control over locally heavy growth of bank vegetation (1, 24, 31, 38). Growths which extend away from the bank or are locally quite heavy can deflect the flow and thus have an adverse erosive effect on the downstream bank or on the opposite streambank. The narrower that the stream is, the more likely are such adverse effects, including constriction of the channel waterway and increased velocities. Management therefore includes removal of excessive growth from streambanks. A dense vegetation of moderate size should be retained on the streambanks to provide protective roughness that reduces local velocities. Both at the face and top of the bank tree growth must be managed. Tree roots provide a stabilizing matrix for the soil, but trees that topple due to winds, old age, or floods have the potential to cause local scour and undermining of the bank.

VEGETATION COMBINED WITH MECHANICAL METHODS

Vegetation can be effectively combined with a number of mechanical techniques for slope stabilization. This is best done where vegetation alone is insufficient to stabilize the bank because stream velocities

are excessive, a vertical streambank is present, or there is some other constraint. Generally in this type of combined system, vegetation is used on the slope above low water, the mechanical technique is used below this vegetation, or the mechanical device will be situated to induce sedimentation at the toe of the slope and thus allow plantings to gain a foothold at this point. With time, the degree of protection increases as the plants grow and spread.

Mechanical slope protection used in conjunction with vegetative protection can be classified as continuous protection or localized protection. Continuous protection normally involves a revetment to stabilize the base of a streambank. Localized protection typically involves dikes and jetties to induce sediment deposition. Both approaches are effective under critical circumstances, as with high-velocity flows. For less severe conditions there may be less justification for their use, with greater reliance placed on natural means of bank stabilization alone. When they are used conjunctively, the type of protection chosen is a function of stream parameters, material availability, and cost. In critical situations, revetments are more effective than jetties.

Revetments

Revetments are usually established below the low-water lines over continuous zones spanning the critical erosion areas, with vegetative growth established above them. They are well suited to locations where near-bank velocities are very large. They serve to stabilize the toe of the streambank so that vegetation can become established farther up the

slope. They are often used where localized protection from dikes or jetties is insufficient due to excessive stream velocities (this varies with location and no specific velocities are cited).

Many types of permanent revetments have been used (4, 5, 11, 12, 13, 15, 16, 18, 20, 21, 27, 30, 34, 36, 37, 38). These include concrete, asphalt, riprap, gabions, and sacks filled with soil-cement. Riprap is the most common. Where suitable material is locally available, it is also the most economical. All such slope protection should be keyed into the bank at the toe and the ends to prevent scour, undercutting, and endcutting. The zone above the permanent revetment is then planted or otherwise protected with vegetation. Figure 5 illustrates a composite revetment of this type.

A newer type of revetment is composed of old car tires. These may be filled with soil or be left to fill with sediment after placement on the riverbank. They are then planted and grassy vegetation soon overgrows the area, as demonstrated on the Washita River, Oklahoma (2).

Dikes and Jetties

Dikes and jetties used with vegetative management are pervious structures that slow the adjacent river velocities so that sediment will settle out of the flow passing through or around the structures. Deposits form during periods of high water and sediment transport. Natural plant growth will establish itself within a relatively short period of time after a sufficient sand bank is formed. Planting of such an area will speed up the stabilization process. Tree deflectors and tree jetties, both of which were previously considered, can also aid in the formation

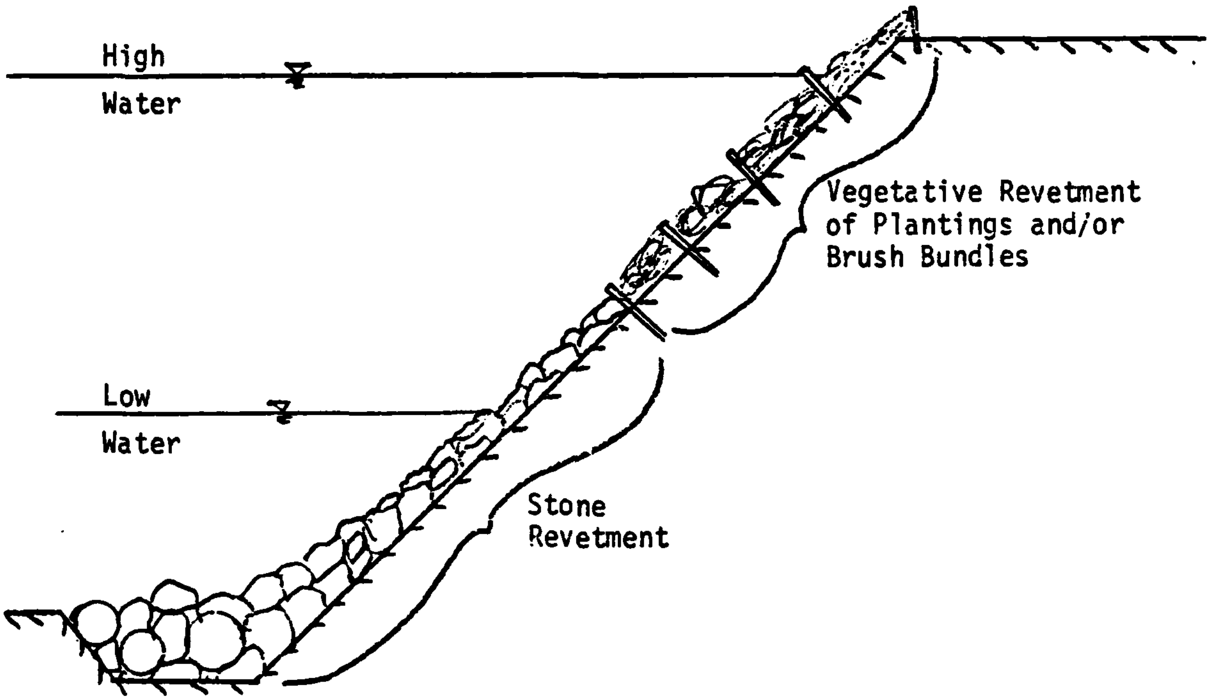


Figure 5. Combination Vegetation-and-Stone Revetment

of sand deposits. Bank sloping behind pervious dikes and jetties can allow vegetation to get an early start. The effectiveness of specific systems is dependent on local conditions. None are foolproof.

Some techniques applied to a broad range of streams are noted here (9, 10, 13, 15, 17, 29, 36, 38, 40). (1) Timber piles can be placed in single rows, staggered rows, clumps, or multiple row clumps. It is often necessary to protect the bottom of piles from scour with riprap or protective matting. (2) Steel jetties include jacks, tetrahedrons, and other similar configurations of steel structures. Jacks are probably the most common. They are composed of three pieces of angle iron welded at the center, with wire strung throughout. Jacks can be placed in a row along the bank or, with the use of flow retards, a row can be extended out into the current. Trees and brush can be placed behind these rows to induce sedimentation. (3) Pipe and wood fencing backed by trees and brush can offer effective riverbank protection. (4) Steel railroad rails used as fencing and backfilled by trees and brush have a similar effect.

Numerous types of impervious dikes are in common use with vegetative management. As continuous walls over their length, they do not allow through-flow at reduced velocity, which would induce sedimentation. Instead, they deflect the flow and cause eddies and secondary currents with associated deposition zones. These require more effort to construct than the simpler pervious structures and are often much more expensive, although there is some feeling that the impervious structures are more efficient (15, 36). However, scour will be more severe along the face of

an impervious dike than a pervious dike. In the first case the flow is entirely deflected and secondary currents will move sediment away from the base of the wall. In the second case the deflection is less and through-flow allows sediment transport into the vicinity of the wall where diminished velocities will allow sediment to settle out.

RIPARIAN LAND MANAGEMENT

Land management techniques to help control runoff and soil erosion have long been known and were even used in some forms by early civilizations. The soil conservation movement of the 1930's, triggered by the drought years of the late 1920's and early 1930's, did much to stimulate the development of land management for erosion control in the United States. This has focused more on upland areas and small streams than on the banks of the larger rivers, where mechanical/structural techniques were often applied.

Riparian land management has received much less attention than that given to lands away from streambanks. This may reflect economic constraints, lack of knowledge of available techniques, or simply a lack of concern.

In urban and suburban areas, threatened riparian lands have generally been protected by structural techniques due to a greater willingness to spend money to protect the more expensive investments found there. But the benefit-to-cost ratio is not as favorable in rural areas and structural protection is much less likely to be found there. Often, the riparian lands away from settlements consist of low-lying wooded floodplain lands, flooded sufficiently often that little capital investment has

been made in land improvements. Agricultural lands may be cultivated right to the river bank, but again the capital investment is usually relatively small. Economic constraints and lack of sufficient incentives tend to limit the amount of streambank protection in rural areas.

Both in settled areas and in rural areas there are measures which can be undertaken by landowners to provide sound management of riparian lands and to reduce streambank erosion. The most important contributions of these measures are the slowing of direct runoff, the increase of rainfall infiltration to the soil, and the prevention of activities that damage the vegetative protection of the streambank.

Vegetation zones such as strips of brush and trees along a streambank offer one effective means of riparian land management. For example, a strip 25 to 50 feet in width adjacent to the bank was recommended for small streams in Utah (14). Such zones of riparian vegetation help to stabilize the banks through the root structure that develops, the reduction of upland erosion, and the provision of a windbreak so that trees near the bank are less prone to toppling. Typical vegetation used in such zones in various parts of the country include grasses, shrubs, cattails, sedges, willows, russian olives and other types of trees (28).

Several farming practices reportedly influence the conditions of streambank stability (1, 7, 13, 14, 26, 35, 36). For instance, cultivated crops should not occur on the banks themselves, but should stop some distance away. Otherwise, the disturbed raw soil along low spots at the bank may be subject to erosion by storm runoff and the formation of small gullies through the bank that locally increase the susceptibility of the

streambank to erosion. Upland farm areas can also be managed to help control this situation. Terracing of uplands stops the formation of gullies, thereby reducing surface runoff and erosion. Hilly ground can be converted to permanent pasture to accomplish the same goals. Strip cropping and contour farming are also quite beneficial.

Erosion and stabilization problems can also occur if irrigation practices are not carefully managed. Good management includes keeping irrigation ditches a safe distance away from streambanks and maintaining a close watch over the amount of irrigation water being applied. Over-irrigation can saturate a streambank at a time when the river level is low; this will result in large seepage forces at the bank and can induce erosion there. It has also been found that the addition of drainage ditches and drain tiles, as well as farm ponds, at strategic locations can reduce the overall runoff effects and help protect streambanks from becoming saturated.

Livestock grazing and watering control are also important parts of riparian land management that can be undertaken in order to reduce the risk of bank cutting and erosion (7, 13, 14, 24, 31, 32, 33, 34, 35). Pasture and rangelands should not be immediately adjacent to the stream at erosion-prone locations. Livestock can over-graze and trample the protective streambank vegetation, including shrubs and small trees. Controlled livestock watering could also be implemented, so that trails do not develop at undesired locations that could enhance gully formation, concentrated erosion and streambank disturbance. (Human traffic can produce similar problems.) Selective fencing can be both effective and

workable for livestock control. Three-to-four strand barbed wire will hold cattle and horses, but woven wire is needed to contain sheep and pigs. However, annual fencing maintenance and repairs are needed.

Land use management and management policies on a broader scale, away from the immediate streambanks, can also be effective in erosion control. While not giving a particular riparian landowner immediate effective help, such owners have a citizen's role in the evolution of such policies and should be aware of beneficial management practices.

Such land use activities include general watershed management to control and retard runoff from upland areas, so that lands closer to the stream can drain first after a storm, thus reducing rather than increasing the peak streamflows. Urban developments pose particular problems in this regard. The development of large impermeable surfaces and of efficient stormwater sewer systems in urbanizing areas accelerates the runoff process and results in larger-than-natural peak streamflows. Zoning to control the locations of urban growth can help alleviate some runoff and erosion problems. When urban centers lie in downstream reaches of a river, efficient drainage systems that quickly carry storm runoff to the river may be desirable; when urban centers lie upstream or away from the river, runoff detention and retarding structures may be more beneficial in controlling peak streamflows. Ponds, sediment basins, dikes, erosion-control spillways, lined channels and diversion canals are among the measures available to obtain given goals (11, 19).

In possible conflict with attempts to reduce erosion damage by reducing flood peaks is some evidence that the greatest damage to

streambanks occurs at less than flood stage and that prolonged high waters cause more serious erosion than flash floods (27,32). However, information on water table levels is not given in these situations to allow identification of the role of the relative height of bank saturation and river level on bank erosion.

SUMMARY

The available literature appears optimistic in showing that bank shaping, vegetative management, and riparian land management are all effective, to differing degrees, in stabilizing streambanks. However, under severe circumstances these methods are not sufficient to completely control erosion and bank cutting. In such cases, mechanical/structural means are required. It would appear, then, that an effective riverbank management scheme should combine these four methods as needed to fit local conditions. The final scheme chosen will be dependent upon various stream characteristics such as width, depth, sediment load, and velocity. Regardless of the final method selected, maintenance of the system will be a necessity.

LITERATURE CITED

The information sources listed below were used to prepare the foregoing literature review. Many of these references are given with a parenthetical identification also shown at the end of the citation. Such parenthetical notation refers to the section and page number where the abstract for this reference will be found in the Literature Search on Natural Means of Streambank Stabilization, prepared by P. C. Klingeman in January 1975 for the Portland District, Corps of Engineers, Department of the Army. Other literature abstracted in that report was also examined but not referenced here as being less relevant, less specific, or repetitive of information given in those references that had already been examined.

1. Altpeter, L. S., "Use of Vegetation in Control of Streambank Erosion in Northern New England," J. of Forestry, v. 42, No. 2, Feb. 1944, 99-107 (J 57).

2. Anderson, E. J., "Old Tires Retread Worn Streambanks," Soil Conserv., v. 34, No. 11, June 1969, 256-7 (J 94).

3. Anon., "Heavy Jute Mats Aid Erosion Control." Eng. News-Record, v. 169 No. 1, July 5, 1962, 57-8 (J 55).

4. Anon., "Soil-Cement Revetment Moves," Eng. News-Record, v. 123, No. 15, 1939, 53 (J 52).

5. Anon., "New Riprap Idea at Ice Harbor Dam," Western Construction, v. 32, No. 1, January 1957, 114 (J 117).

6. Bagnold, R. A., Some Aspects of the Shape of River Meanders, Professional Paper 282-E, U. S. Geological Survey, Washington, D.C., 1960, 135-144.

7. Barnes, R. C., Jr., "Streambank Erosion," Soil Conserv., v. 33, No. 6, Jan. 1968, 126-8 (J 92).

8. Blench, T., Regime Behavior of Canals and Rivers, Buttersworths Scientific Publications, London, England, 1957, 168 pp.

9. Byers, W. G., "Stabilization of Canadian River at Canadian, Texas," Proc. ASCE, J. Waterways & Harbors Div., v. 88, No. WW3, Aug. 1962, paper 3214, 13-26 (J 18).

10. Church, R. P., "Angle-Iron Structures Tame River Current," Soil Conserv., v. 33, No. 6, Jan 1965, 131 (J 93).

11. Corps of Engineers, Hydraulic Design of Flood Control Channels, Manual EM 1110-2-1601, Department of the Army, Corps of Engineers, Washington, 1970, 66 pp.

12. Crews, J. E., "Bank Stabilization in Susquehanna River Basin," Proc. ASCE, J. Waterways & Harbors Div., v. 96, No. WW1, Feb 1970, paper 7061, 87-95 (J 27).

13. Edminster, F. C., W. S. Atkinson, and A. C. McIntyre, Streambank Erosion Control on the Winooski River, Vermont, U.S.D.A., S.C.S., Circular No. 837, 1949, 54 pp. (R 38).

14. Felker, R. H., "Streambank Control," Soil Conserv., v. 12, No. 5, Dec. 1946, 114-17 (J 85).

15. Fenwick, G. B., State of Knowledge of Channel Stabilization in Major Alluvial Rivers, U. S. Army Corps of Engrs. Comm. on Channel Stabilization, Tech. Rep. 7, Oct 1969, 261 pp (R 37).

16. Finch, H. A., "Earth-Cement Mixture in Sacks Used for River-Bank Revetment," Eng. News-Record, v. 122, No. 19, May 11, 1939, 659 (J 51).

17. Frogge, R. R., "Stabilization of Frenchman River Using Steel Jacks," Proc. ASCE, J. Waterways & Harbors Div., v. 93, No. WW3, Aug 1967, paper 5396, 89-108 (J 25).

18. Hansen, E. A., Stabilizing Eroding Streambanks in Sand Drift Areas of the Lake States, U.S.D.A., Forest Service, Research Paper NC-21, 1968, 12 pp (R 34).

19. Holeman, J. N. and E. F. Sauer, "Conservation in a New Town," Soil Conserv., v. 35, No. 2, Sept. 1969, 35-8 (J 95).

20. Lamberton, B. A., "Revetment Construction by Fabriform Process," Proc. ASCE, J. Construction Div., v. 95, No. CO1, July 1969, 49-54 (J 6).

21. Leep, R. W., "California Soil Conservation District Streambank Stabilization Program," J. Soil & Water Conserv., v. 20, No. 1, Jan-Feb 1965, 29-30 (J 99).

22. Leliavsky, S., An Introduction to Fluvial Hydraulics, Constable, London, England, 1955.

23. Leopold, L. B. and M. G. Wolman, "River Meanders," Bull. of the Geol. Soc. of America, v. 71, No. 6, June 1960, 769-794.

24. Lester, H. H., "Streambank Erosion Control," Agric Eng., vol. 27, No. 9, Sept. 1946, 407-10 (J 2).

25. Li, R. M. and H. W. Shen, "Effect of Tall Vegetations on Flow and Sediment," Proc. ASCE, J. Hydraulics Div., v. 99, No. HY5, May 1973, paper 9748, 793-814 (J 9).

26. Mannering, J. V. and R. E. Burwell, Tillage Methods to Reduce Runoff and Erosion in the Corn Belt, U.S.D.A., A.R.S., Agric. Information Bull. 330, 1968, 14 pp (R 39).

27. McKenzie, G. K., "Low Cost Slope Protection for Levees and River Banks," Proc. 2nd Int'l. Conf. on Soil Mech., Rotterdam, v. 7, 1948, 112-6 (J 96).

28. Miller, R. C. and W. M. Borland, "Stabilization of Fivemile and Muddy Creeks," Proc. ASCE, J. Hydraulics Div., v. 89, No. HY1, Jan 1963, paper 3392, 67-98 (J 7).

29. Oberwager, D., "Teamwork Approach Used in Streambank Stabilization," Soil Conserv., v. 32, No. 10, May 1967, 226-7 (J 91).

30. Parsons, D. A. and R. P. Apmann, "Cellular Concrete Block Revetment," Proc. ASCE, J. Waterways & Harbors Div., v. 91, No. WW2, May 1965, paper 4311, 27-37 (J 21).

31. Parsons, D. A., "Vegetative Control of Streambank Erosion," Proc. of the Federal Interagency Sedimentation Conference, U.S.D.A., Agric. Research Service, Misc. Pub. 970, 1963, 130-6 (R 18).

32. Saveson, I. L. and V. Overholt, "Streambank Protection," Agric. Eng., v. 18, No. 11, Nov. 1937, 489-91 (J 1).

33. Sharp, W. C. and J. Vaden, "10-Year Report on Sloping Techniques Used to Stabilize Eroding Tidal River Banks," Shore Beach, v. 38, No. 1, Apr. 1970, 31-5 (J 84).

34. Silberberger, L. F., "Streambank Stabilization," Agric. Eng., v. 40, No. 4, April 1959, 214-7 (J 3).

35. Southeastern Wisconsin Regional Planning Commission, Floodland and Shoreland Development Guide, Planning Guide No. 5, S. E. Wisc. Regional Planning Comm., Waukesha, Wisc., Nov. 1968, 199 pp (R 11).

36. State Soil and Water Conservation Commission, Streambank Erosion in Oregon, Salem, 1973, 149 pp.

37. Task Committee on Channel Stabilization Works, "Channel Stabilization of Alluvial Rivers," Proc. ASCE, J. Waterways & Harbors Div., v. 91, No. WW1, Feb 1965, paper 4236, 7-37 (J 20).

38. Task Committee for the Preparation of the Manual on Sedimentation, V. A. Vanoni, ed., Sedimentation Engineering, ASCE Manual No. 54 on Engineering Practice, New York, 1975, 518-545.

39. Vanicek, V., "The Soil-protective Role of Specially Shaped Plant Roots," Biological Conserv., v. 5, No. 3, July 1973, 175-80 (J 33).

40. Wall, W. J., "Stabilization Works on the Savannah River," Proc. ASCE, J. Waterways & Harbors Div., v. 88, No. WW1, Feb 1962, 101-16 (J 16).

41. Wallace, M. H., "San Pedro is Less Greedy," Soil Conserv., v. 19, No. 9, Apr. 1954, 202-3 (J 87).

42. Williamson, A. D. and E. R. Simmons, "Old Plant Plays New Role," Soil Conserv., v. 28, No. 2, Sept 1962, 42-3 (J 88).

43. Franklin, J. F. and C. T. Dyrness, Natural Vegetation of Oregon and Washington, U.S.D.A. Forest Service Tech. Rept. PNW-8, Portland, 1973, 110-126.

44. U.S.D.A. Soil Conservation Service, Oregon Standard and Specification Guide for Streambank Protection, Portland.

III. LITERATURE SUMMARY: ACTIVITIES AND PRACTICES THAT AGGRAVATE THE RIVERBANK EROSION PROCESS

SCOPE OF SUMMARY

The previous chapter describes a number of measures that have been undertaken by individual riparian landowners, groups of landowners, and governmental agencies in an attempt to achieve streambank stability by natural means. Also included were some structural techniques in which vegetation played a significant role or which were needed to give the margin of protection that would allow natural methods to be effective. The cited references also stated improper practices or consequences of not taking particular actions. In effect, a series of correlaries to alleviating bank erosion and enhancing bank stability exists describing practices that aggravate streambank erosion, such that these can be given as "opposites" to the recommended methods of bank protection. Because the development of such a set of correlaries involves a restatement of previously cited literature, no additional reference citations are given here.

The statement of activities and practices that aggravate the riverbank erosion process is arranged here in a parallel manner to the discussion of streambank protection techniques in the previous chapter. A semi-outline format is used.

INFLUENCES OVER EROSION

The factors influencing streambank erosion and stability are numerous and varied. They can be identified as falling within two general groups: those which occur due to natural circumstances and those which are primarily man-caused. In other words, natural conditions alone can either enhance the stability or aggravate the erosion of a riverbank. Furthermore, man can exert his influence to fortify, offset, or even counteract a natural process that enhances streambank stability or aggravates streambank erosion. This can happen by accident or willfully.

The natural erosion process is dependent upon such broad factors as climate, vegetation characteristics, soil characteristics, geological history, hydrologic features of the river basin, hydraulic conditions in the river, and the geomorphic features of the river. Each of these broad factors has a large number of subdivisions.

Man-caused influences over the erosion process generally are of an "incremental" nature. That is, an individual can take actions that have a very local effect on one or more of the subdivisional factors but no significant influence on any of the broad factors. Other individuals have similar incremental effects over the erosion process. The cumulative effects of actions taken by a large number of individuals in a given locality will be to cause a noticeable influence on several subdivisional factors and perhaps even a noticeable influence on one or more of the broad factors in that locality. Building on this idea of cumulative effect, groups of individuals taking actions simultaneously at many different localities can alter the broad factors more extensively.

Furthermore, there are some activities that can be taken by groups of individuals or some governmental entity (but not usually by individuals acting alone) at an upstream locality which will have an important influence on several downstream localities. It is evident, then, that to focus on the activities of an individual riparian landowner is to look for possible local effects on specific factors affecting streambank erosion. These are likely to have only limited influence (assuming that the individual landowner is not a large corporation capable of extensive streambank activities).

BANK SHAPING

Improper Bank Alinement

--Too abrupt a transition from the upstream undisturbed natural bank line to the shaped bank, causing the flow to enter the upstream end of the altered zone in a non-alined manner.

--Too abrupt a transition from the shaped bank to the downstream undisturbed natural bank line, causing the flow to be non-alined there and potentially erosive at that bank.

--Too large an angle of flow entry to the shaped bank at the curve, so that little or no improvement over erosive conditions has been gained due to the remaining flow deflection and associated secondary currents.

--Too abrupt and non-smooth a bend curvature, with a sharp angle of flow entry and sharp angle of attack at various points along the bend.

--Too sharp a bend, such that little reduction in the strength of the secondary currents results.

--Too flat a bend, so that the channel behaves more like a straight channel with internal meandering between banks and with bar growth.

--Local curvature reversals within the main curve, causing flow to be deflected from one bank to the other instead of moving smoothly in alinement with the banks.

--Bank irregularities that are created or are left intact, such as (a) false points that deflect the flow or (b) local setouts of the bankline (e.g., due to dumping of material locally on the bank) that deflect the flow and cause eddies or (c) local setbacks of the bank line (e.g., due to local bank shaping or excavation) that cause eddie formation, all of which contribute to the potential for downstream erosion on one or both sides of the river.

Large-Scale Alteration of Channel Alinement

--Straightening of a meandering channel or cutoff of a meander bend without adequate stabilization of streambanks and streambed to make the change permanent and without adequate provision for energy dissipation to compensate for that dissipated in the former bend.

--Change of streambed slope (either steeper or flatter) or of channel length (usually shorter) without adequate adjustments for energy dissipation and sediment transport, leading to streambed degradation with bank undercutting and erosion or leading to streambed aggradation with bar deposition, thalweg meandering and bank erosion.

Improper Channel Width

--Too narrow, such that velocities increase, as does scour directly against the banks and/or against the bed, leading to bank undercutting and caving.

--Too wide, so that bed load deposition occurs to form bars in an aggrading channel with a meandering thalweg (and even branched channels) that can lead to bank attack and erosion by the flow.

--Too wide, so that debris can accumulate on the bars to augment the meandering of the thalweg and bank erosion.

--Too much variability in width, causing zones of local sediment scour and deposition with a shifting thalweg and shifting low flow channel, all encouraging bank attack and erosion by the flow.

--Altered width of the channel at crossings between bends, such that the former crossover pattern of the flow is changed and the flow alinement from one bend to the next is changed in such a way as to aggravate bank erosion.

Improper Bank Slope

--Too steep, due to insufficient bank sloping or to the dumping of material on the bank, causing the flow strength to remain strong against the bank.

--Too flat, so that flow alinement is shifted more onto the bank line at the zone of bank sloping, causing higher velocities to reach the unsloped bank just downstream.

Incomplete Coverage of the Critical Zone

--Incomplete coverage of the critical zone in the vertical direction, due to lack of recognition of the height to which waters may rise and cause scour or of the need for toe protection.

--Incomplete coverage of the critical zone in the longitudinal direction, due to lack of recognition of the critical zone or due to lack of ownership of part of the critical zone (or lack of cooperation among affected landowners).

--Spotty rather than continuous coverage of the critical zone, due to lack of recognition, ownership or cooperation, so that only part of the problem area is dealt with while erosion can continue or be aggravated at unprotected adjacent properties, leading to flanking and failure of the protective works.

Other Considerations

--Inadequate protection for the toe of the bank slope, due to one or more of the above-listed practices or deficiencies.

--Failure to recognize that the untreated natural streambank or channel has improper bank alinement, improper channel width, or improper bank slope for minimizing erosion (i.e., no aggravating practice is involved but there is negligence that may contribute to worsening of a future problem).

VEGETATIVE MANAGEMENT

Existing Natural Vegetation

--Unrestrained growth of dense, clumpy vegetation in localized areas along the streambank that can interact with the flow, causing eddies and flow deflection that results in local downstream erosion of the banks.

--Leaving fallen trees hanging down the face of the streambank into the water, such that the flow is locally deflected by the tree trunk or branches and eddies form that scour the nearby banks.

--Leaving clumpy or otherwise bulky debris stranded on a streambank that otherwise has more-uniformly sized vegetation, thus causing eddies and flow deflections as noted above.

--Removal of top-of-bank vegetation, as by land clearing, so that there is no longer a vegetative network sufficient to reduce the velocities of overbank flood flows and to encourage the deposition of silt, sand and debris.

--Removal of top-of-bank vegetation through land clearing for agricultural or other use, such that the vegetative protection is gone which formerly encouraged infiltration, prevented much surface runoff and prevented the formation of rivelets and gullies down the face of the streambank.

--Failure to remove isolated large vegetation, such as trees, which are toppling and whose roots are pulling out of and loosening the soil.

--Bank filling with earth or debris that covers the existing vegetation and creates too steep a bank face for new vegetation to be established.

--Failure to take measures to protect existing vegetation in zones of sparce growth or erosion damage where the soil has been or may become directly exposed to strong currents in the absence of the former vegetative cover.

--Felling trees into the river and leaving them in such a manner that snags and debris accumulations occur in the river near the streambank, causing the flow to deflect toward the bank.

--Failure to remove or relocate snags and debris accumulations from the river near the streambank, thus allowing flows to continue to be deflected toward the bank.

Planted Vegetation

--Inadequate type of vegetation for the environmental conditions encountered at a particular location on the streambank (inundation, bank steepness, sunlight, soil type and texture, etc).

--Too wide a spacing of vegetation, creating a low-density growth with exposed soil between individual plants or groups of plants.

--Too close a spacing of vegetation, leading to crowding and inadequate growth of plantings.

--Planting in a parallel-row pattern instead of a staggered pattern or randomly, such that inundating flows can develop currents along the rows instead of being blocked and retarded by vegetation, as would occur with staggered or random planting.

--Insufficient maintenance of planted vegetation, such as lack of replanting, thinning, or length control.

--Use in conjunction with bank filling where the bank filling creates too steep a slope and the weight of the growing vegetation causes soil slippage and spalling.

--Failure to plant vegetation where natural vegetation has been removed or has died and the root system is deteriorating so that it no longer gives soil-holding benefits.

Vegetative Structures

--Improper placing of vegetative structures, such that no protection is gained or that the structures cause flow deflections and eddies that act against the banks to cause scour where less or no scour formerly occurred.

--Insufficient periodic maintenance of vegetative structures after their installation.

--Improper types of vegetative structures, such as felling large trees on a bank that is protected by short vegetation, thus creating groups of eddies that encourage rather than discourage local scour of the original bank vegetation.

--Use of relatively non-permeable forms of vegetative structures where a more permeable structure would better encourage sediment deposition and allow the establishment of bank vegetation.

Other Considerations

--Lack of maintenance of non-vegetative structures that, together with streambank vegetation, protect the riverbanks.

--Inadequate size or anchorage of protective material placed on a bank, causing its loss from the bank and potential accumulation in the stream near the bank toe to aggravate local scour.

RIPARIAN LAND MANAGEMENT

Relative to Farming

--Clearing top-of-bank vegetation to the edge of the existing bank for cultivation purposes, thus increasing the likelihood of direct surface runoff that can erode the face of the bank.

--Not leaving a wide enough vegetative strip at the top of the bank so that a continual buffer to direct runoff is maintained over the years as slow bank erosion causes the bank line to retreat into the buffer zone.

--Cultivation to within close proximity of the bank which cuts up the vegetation and its root structure and facilitates top-of-bank scour during periods of high water and overbank flow.

--Over-irrigation near the top of the bank that leads to saturation of the bank at times when the river level is quite low, causing large seepage gradients that can result in bank caving.

--Use of unlined irrigation ditches close to the top of the bank such that saturation of the bank can occur, as due to over-irrigation, with similar results.

--Placing drainage lines or ditches at the bank in such a manner that local scour and gullying can occur.

Relative to Livestock

--Allowing livestock to trample and destroy protective vegetation (both foliage and root structure) on the top, face or base of streambanks.

--Allowing livestock to trample and weaken the erosion resistance of protective soil at the base of banks that are subject to or have the potential for serious erosion.

--Allowing animal trails to develop into gullies in locations where streambanks thereby become exposed to erosive attack by the higher flows.

Activities Not Specific to Agriculture

--Clearing top-of-bank vegetation to the edge of the existing bank for non-agricultural uses at locations where any increase in surface runoff would be damaging to the streambanks.

--Narrowing the widths of protective tree belts along the top of streambanks to such an extent that windfalling of trees is likely, resulting in flow deflections and eddies at the streambank whenever such trees topple down the bank.

--Increasing the amount of direct surface runoff in drainage channels with unprotected exits.

--Decreasing the amount of runoff infiltration to the soil.

--Allowing trails to develop along the top of the bank, down the face of the bank or along the base of the bank at those locations where the resulting loss of vegetation and exposure of the soil would result in greater erosion from streamflow.

--Construction of river-related structures (intakes, diversions, bridges, etc.) that alter flow patterns and local sediment transport can either aggravate or alleviate the riverbank erosion process. Inadequate hydraulic design or improper placement of these structures can aggravate bank erosion in the local vicinity and even for several hundred feet downstream.

--Wave action against exposed streambanks from powered boats.

IV. RIVER FEATURES PERTINENT TO STREAMBANK EROSION IN THE WILLAMETTE RIVER AND PRINCIPAL TRIBUTARIES

The main-stem Willamette River downstream from Eugene and the lower reaches of all principal tributaries can be classified as "meandering" in their behavior. This classification carries with it a set of geomorphic and hydraulic behavior characteristics that bear directly upon erosional processes. Therefore, in order to review the available techniques and methods for natural streambank stabilization with respect to representative field situations observed in the Willamette Basin, it is most important to understand these behavioral characteristics. In this chapter, these characteristics and features will be discussed to set out the conditions under which streambank stabilization measures must serve.

RIVER MEANDER BEHAVIOR

Occurrence of Meanders

Meanders occur because part of the water's energy, as it moves downriver to progressively lower elevations, is expended not only to overcome the frictional resistance of the channel boundary but also to scour out streambank and streambed material and to transport this in suspension or as bed load (dragged and rolled along at the bed). This is especially the case during floods when a great amount of river energy is available. The process occurs in alluvial channels--channels having boundaries formed of alluvial deposits laid down by the river at some time in the historic

or geologic past. The scoured sediment is transported to zones of weaker streamflow where it can deposit. This scour and deposition alters the channel boundary configuration.

Meanders are influenced by several factors. These include the general valley slope, the magnitude and variability of magnitude of river water discharge, the types and quantities of sediment transported by the river, the resistance of the banks to erosion, and the existence of transverse (to channel direction) disturbances to the streamflow.

On the floor of the Willamette Valley the above factors favor meandering not only of the Willamette River and its larger tributaries but also of the lesser streams. The valley slope is not great; stream discharges exhibit great variability of magnitude; the valley sediments are generally readily transportable by flowing water, at least during periods of large discharge, once disturbed; the banks possess variable resistance to erosion but can be eroded under the vigorous attack of river currents; and many disturbances to streamflow occur that set up transverse currents.

The size of a meander (its length and width) is dependent upon water discharge. A meandering channel which has been shaped by smaller discharges could be reshaped to correspond to the configuration governed by bigger discharges if river flow is periodically increased to the higher values.

Characteristic Features of Meanders

Certain features of meanders are characteristic. The channel boundary consists of alluvial material which can be described as erodible. Meanders are best formed when streambanks are neither too easily eroded

nor too resistant. Secondary currents (described by velocity components in the cross section plane perpendicular to the channel axis) occur in addition to the primary current along the longitudinal axis of the river, resulting in a complex spiral or helical flow. Scour and deposition of sediment occur in different locations in the erodible channel. Scour is usual at the outside (concave) bank of a bend or curve of river channel. The channel is deep near this bank. Deposition is usual at the inside of the bend (convex bank). Hence, the channel is shallow here with a bar (point bar) that becomes progressively more exposed as streamflow diminishes. Scour and deposition may both occur at the crossings between successive bends. This happens at differing times dependent upon the magnitude of streamflow. Crossings are shallower than concave bends of a meandering river and may contain riffles at low water stages.

Figures 6 and 7 show several of the features described above and in following paragraphs.

Stability of Channel Location

The permanence of the channel location for a meandering river is a relative condition. Over a period of several decades, a meandering channel is unstable in its location. Maps spanning more than a century, from 1852 up to the present, show that the channel of the Willamette has migrated back and forth laterally across the valley within a wide meander belt several times the actual water-surface width of the river. Only the lower Willamette River, downstream from River Mile (RM) 50 near Newberg has stayed fairly constant in position over this period. Elsewhere,

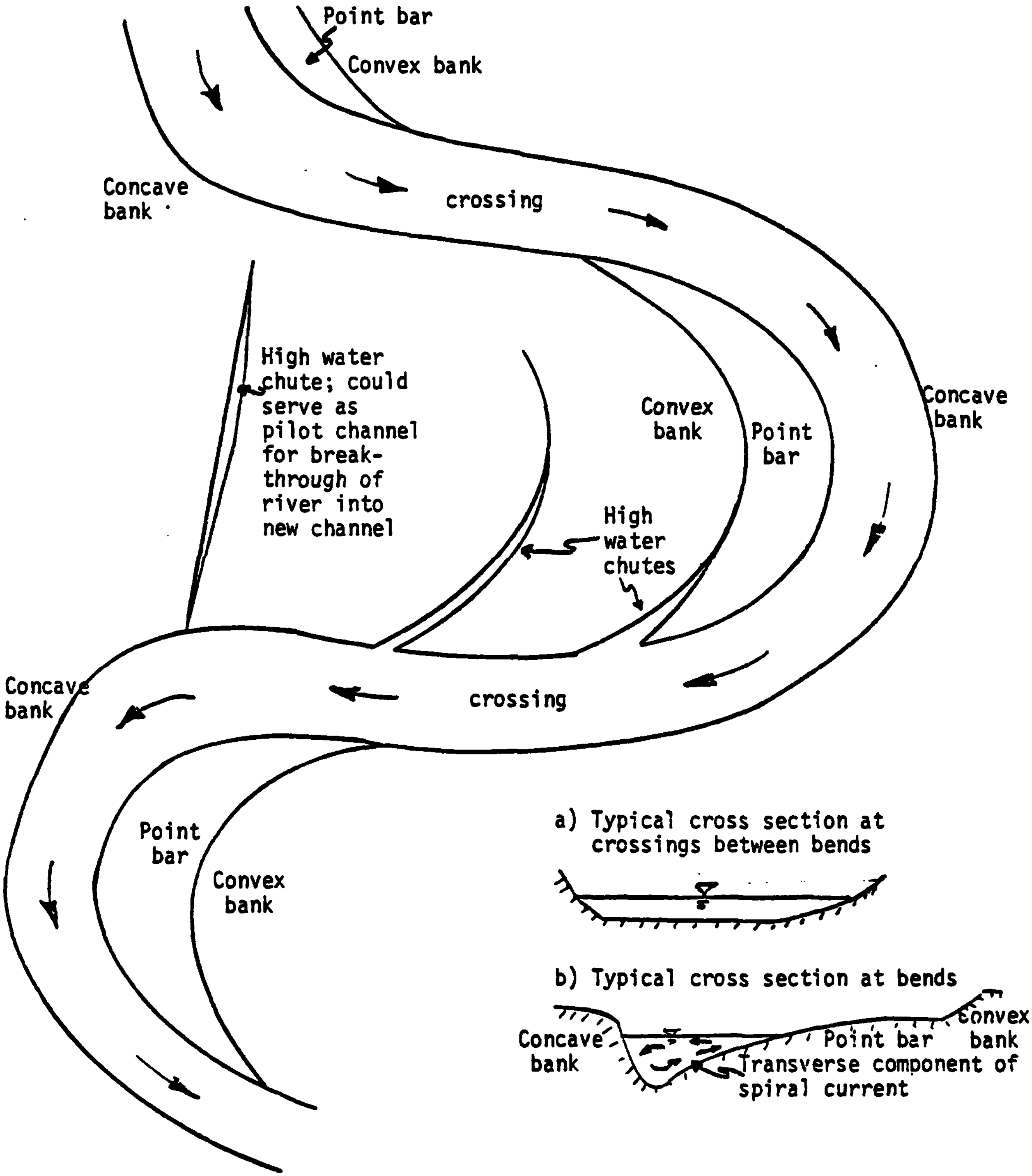


Figure 6. Features of Meandering Rivers at a Meander Loop

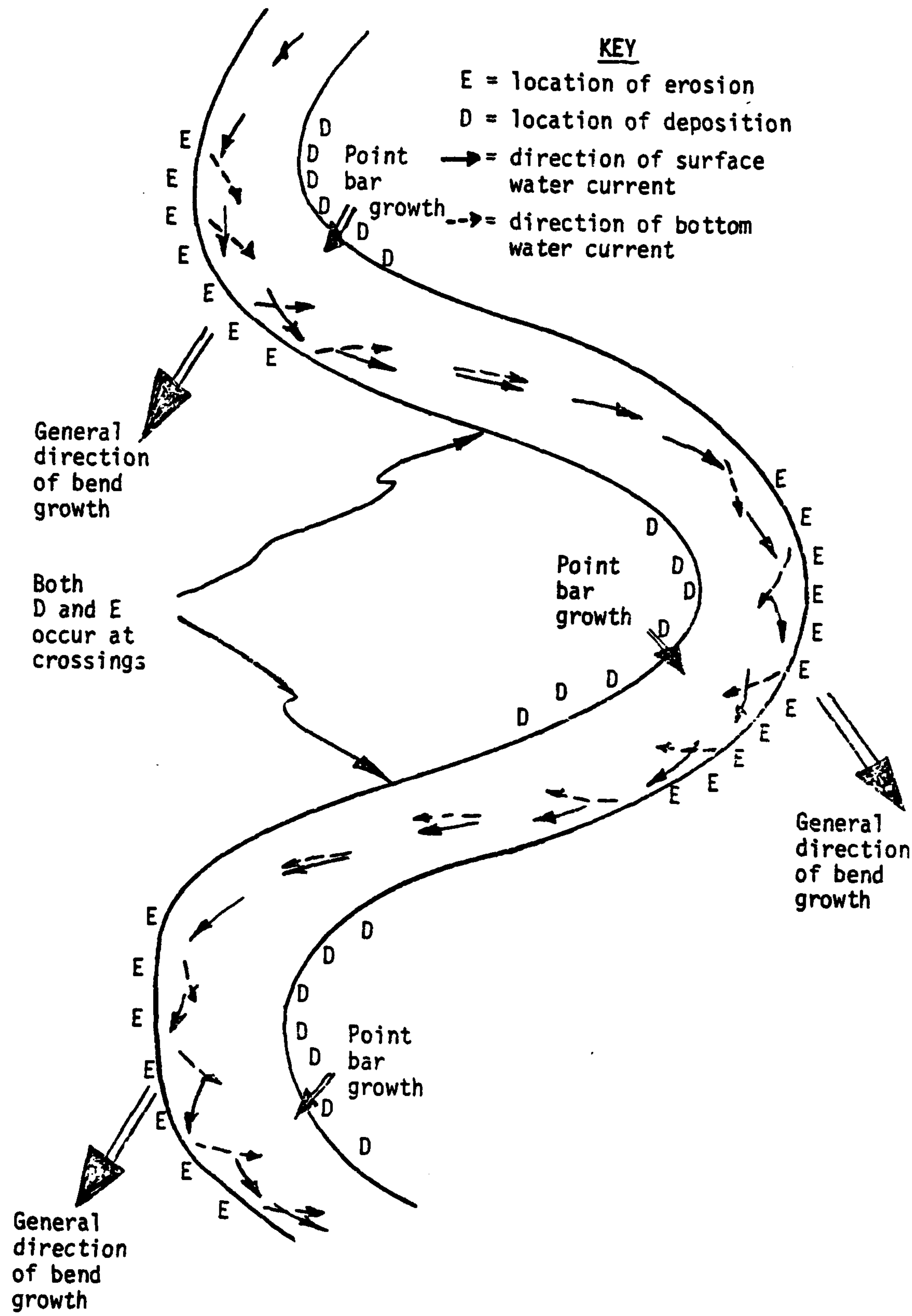


Figure 7. Erosional and Depositional Patterns in a Meandering River

segments of former channels are evident from aerial photographs at distances of up to several thousand feet from the present channel.

Over a shorter period of up to several years, the channel position at a given location can remain stable and well-behaved, due to a brief local dominance of resisting ability of the channel over erosive ability of the water. However, the channel position can change rather abruptly through a sequence of events in the short order of time of one or several severe floods. It may also change more gradually and progressively due to bank erosion from periodic high water, even in the absence of a major flood.

Any meandering river tends to extend and perpetuate the meander system by the erosive action of the streamflow at the outside of each bend and the deposition of sediment at point bars. Deposits at crossings or in the form of alternate bars along straight stretches of the river can also lead to bank erosion and the growth of a meander pattern. Any moderate departure from straight flow in a straight channel can lead to the eventual development of a meander pattern if the channel banks are erodible.

Channel instabilities most usually occur at upstream points and are propagated downstream. This happens when a change in channel bend upstream changes the flow curvature entering the next bend downstream and sets in action greater scour there, which in turn influences downstream bends. This effect is eventually damped out with distance downstream or overriden by other influences or events.

Sediment Scour and Deposition

The scour and deposition of sediment in the meandering rivers of the Willamette Basin have a definite relation to the streamflow variations caused by a flood. Scour at concave banks is usually most severe during flood periods, unless the banks are low and the stream goes out-of-banks without much increase in streamflow. Deposition occurs at convex banks and at crossings during floods. At low streamflows, scour tends to occur at crossings. At low flows, deposition tends to occur in deep pools near the concave side of bends. This does not compensate for scour there during floods. Therefore, the net effect is a progressive outward and downstream cutting of the concave bank, leading to elongation of the curve and meander loop.

Probably most outer-bank caving and loop elongation occurs during the falling stages of floods. During the rise and peak, the thread of maximum velocity tends to shift from the low-water meander channel toward a less-looping flow along the general axis and slope of the valley. This tendency, plus the increased velocity and discharge, causes short-cutting of the flow across the convex bars and can result in partial scour of the bars. As the water level begins to fall, the sediment transport capacity is reduced and the bed load begins to redeposit. The convex-bank areas receive the greatest deposits, due to secondary currents, restoring and enlarging the former bars. This directs the still-high flows sharply against the concave bank, causing undermining and caving.

Progressive Changes at Meander Loops

Progressive changes normally occur at a large bend (loop) in the meandering Willamette River and in the lower reaches of its tributaries. Outer-bank scour and inner-bank deposition cause meander loops to gradually extend outwards and elongate while drawing closer at the neck or base of the loop. A more pronounced scour occurs at the downstream portion of the concave bank than upstream of the mid-point of a bend. This causes meander loops to slowly migrate down-valley, the rate of movement being primarily influenced by river discharges and their durations. Periods of high water allow the most rapid shifting of channel position. Often, abrupt and localized changes of channel alinement occur. These are due to channel changes that have happened a short distance upstream or downstream, such as an abrupt change of alinement due to the cutting-off of a bend, and to the occurrence of local "fixed points" ("hard points") along the Willamette and its meandering tributaries--bed or bank areas that resist scour and remain permanent in location over long periods. These occur where bedrock outcroppings, cemented gravels, or hardpan composed of consolidated fine-textured and semi-cohesive soils are exposed at the river bank.

River bends in the Willamette Valley may elongate to some point of maximum sinuosity. Chutes eventually develop across low convex-side areas during high flows or due to changes in upstream flow alinement. A sudden cutoff may develop if the main flow breaks through the neck of the loop. This causes a new channel to develop while the old channel is abandoned, still carrying flood flows but gradually shrinking due to

sediment deposition, leaving only an oxbow lake. The combined outer-bank scour and inner-bank deposition begin anew for the cutoff channel, so that a new loop might begin forming there.

The natural cutoff need not be delayed until the loop reaches its maximum sinuosity. Overbank flooding can cause the natural scouring of a pilot channel, which may enlarge rapidly if high flows last long enough. Similarly, changes in the upstream alinement of a channel may have an effect on a downstream loop. When a breakthrough occurs, the river locally shortens its flow path. This produces an energy imbalance which works its influence in both the upstream and downstream directions. Upstream, streambed scour begins which can lead to deepening of the channel. But, because of varying resistance of the bed and banks, sooner or later bank caving and changes of channel curvature will occur. Downstream, the breakthrough will cause flow with a different alinement than before. This will immediately change the locations of bank cutting and bar deposition in the downstream channel. The disturbance will be felt for a distance downstream involving perhaps the next two or three bends. Farther downstream, new influences occur or new conditions are met which either dampen out the disturbance or change its nature.

Description of Channel Curvature

The sharpness of a river bend varies with the water level and discharge. This is because the concave bank is relatively steep and high while the convex boundary is normally low and flat. Hence, as discharge increases more of the flow moves across the convex side of the channel.

A relative bend curvature (R/b) can be defined to describe the sharpness of a bend, based upon the width of the channel at the water surface (b) and the radius of the waterway (R). This definition is illustrated in Figure 8. The ratio increases as water level drops, due to the narrowing of the water surface.

<u>Channel Bars and Islands</u>

Bars are a common part of the bed configuration of all meandering rivers in the Willamette Basin. River bars are sizeable bed forms generated by the flow that occur within the confines of the highwater banks and result from sediment deposition. Bars commonly have lengths that are of similar size to the channel width or greater. Their surfaces normally extend above low water but below the levels of the highwater banks.

Several different types of bars may be observed along the Willamette River and its tributaries: point bars, alternating bars, transverse bars, mid-channel bars, and tributary bars.

Point bars are sediment deposits that occur on the convex sides of channel bends. Their shapes vary and are strongly influenced by bend sharpness and changing flow conditions. As the channel location at a bend shifts, the top and back of the point bar receive deposits of finer-sized sediments which gradually increase the local surface elevation. The coarse gravels and cobbles that initially deposited there may become overlain by quite distinct layers of different-textured material, the uppermost layer being predominantly in the size range of silt and clay and eventually becoming several feet in thickness.

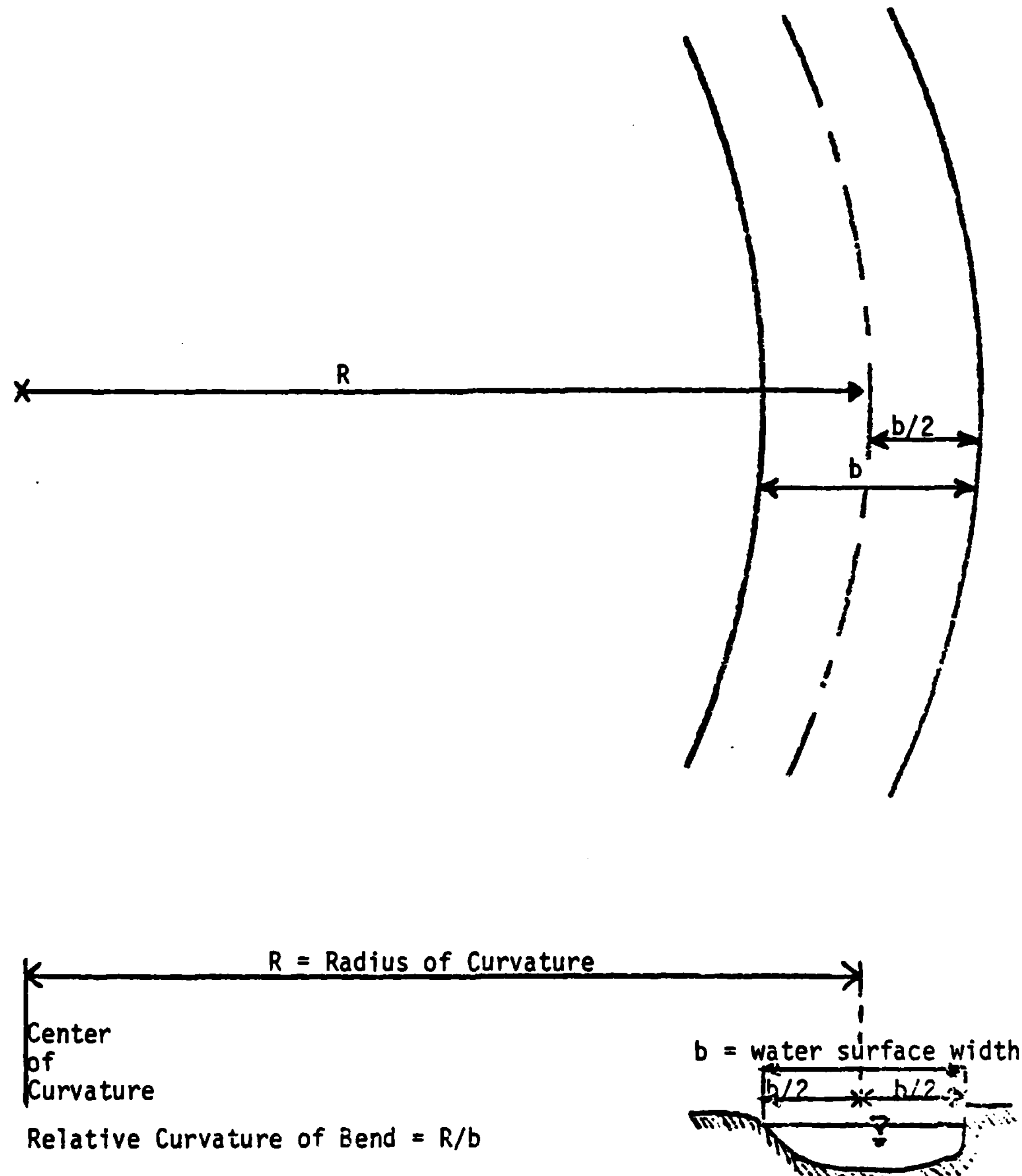


Figure 8. Definition Sketch for Relative Bend Curvature

Alternating bars and transverse bars are encountered in relatively straight reaches or in very gradual curves of the river. Alternating bars are distributed along the channel in an alternating manner near opposite channel banks. Their lateral extents are about one-third or one-half of the channel width and their lengths are similar to the channel width. Transverse bars occupy nearly the full channel width and may occur as isolated or periodic forms along the river.

Alternating bar systems cause a low-water meander pattern of the thalweg (main thread of flow) within the reach and serve an energy-dissipating role. They may remain stationary in location or slowly migrate downstream due to a combination of scour and deposition. Well developed alternating bar systems are more readily seen in the principal tributaries than in the main stem of the Willamette.

Transverse bars remain substantially submerged during low flows because of their width being nearly that of the channel. In the downstream reaches they may only be evident as shoal areas. In the upriver reaches the low flows may incise them in one, two or three places to cause shallow riffles or rapids between low bar crests.

Mid-channel bars are similar to transverse bars, except that the exposed bar is away from both banks and deeper flows occur on each side. Mid-channel bars are to be found in various parts of the Willamette system. They sometimes form as a result of debris snagging on a shallow transverse bar or at a shallow crossing between successive bends, forming a relatively protected wake zone where sediment can accumulate. They may form as the result of bank erosion that produces a wider than normal

channel locally or otherwise causes stronger threads of flow near both banks than in mid stream.

Tributary bars occur immediately downstream from and at the same bank as points of lateral inflow into a river from a tributary stream. While not generally evident along the Willamette River, tributary bars can be seen along the principal tributaries, such as at Wiley Creek below Foster Dam.

River bars are often incorrectly referred to as islands. All sediment deposits between highwater banks that have a shape deviating from a flat bed can be considered to be bars. An island, in comparison, is defined as a tract of land completely surrounded by water, not large enough to be a continent. The term island is applicable to a tract of land that was formerly outside of the channel but, due to channel changes, subsequently become surrounded by water. Many tracts of land along the banks of the Willamette carry the name "island" although not now surrounded by water. Most were apparently named at times when the lands had indeed been islands.

Multiple Channels

In some locations, the Willamette River and its tributaries may divide into multiple channels (not merely a flow division about mid-channel bars, as at times of low water in the stream). If a split into two channels occurs with an extensive tract of land between (an island), the meandering characteristics already described might take place separately in each channel. The island near the mouth of the McKenzie River between RM 174.5 and RM 176.3 provides an excellent example of this.

If the island is long and wide, the meander activities can be relatively (but not absolutely) independent--with common influences at the upstream and downstream junctions and with a dependency upon the relative amounts of flow in each channel. One of the two channels might experience much more extensive meandering than the other. It is also possible that during a flood causing out-of-bank flow, the water level in the channel on one side of the island will differ from that in the channel on the other side. In this situation, there could be an across-island flow from one channel to another. This could be similar to the cutoff flow described for meander loops. Such flow could produce small floodwater channels and could lead to shifts in channel location.

River Junctions

The vicinity of the confluence of two large meandering alluvial rivers is a zone of channel instability marked by shifting channels and changes of the point of juncture. Where the land near the confluence is relatively flat, the size of the zone of channel changes may be appreciable. The conditions at the mouths of the McKenzie and Santiam Rivers illustrate this type of situation.

Where the main river is considerably larger than the tributary, events occurring in the main river will normally dominate the behavior pattern in the zone of juncture of the two streams. At the mouth of the Long Tom River (before and after its rechanneling in connection with construction of Fern Ridge Dam), for example, the Willamette appears to have continued to meander primarily in response to conditions within that river rather than due to influences exerted by the Long Tom River.

The channel processes described for a single meandering channel are applicable in more complex form at the confluence of two rivers. Each river approaching the juncture meanders within its own floodplain. The complexity is caused by variable differences in the flows of both streams: both may be in flood simultaneously; both may be low simultaneously; one may be in flood while the other is low; or both may be in flood but reach their crests out of phase. Thus, at the confluence of two rivers one would expect severe channel shifting and, possibly, the development of multiple channels. The rapid changes attendant with individual floods would leave remnant channels behind which might again become principal channels after subsequent floods.

HYDRAULIC BEHAVIOR

Flow Velocity and Boundary Shear Stress

The water velocity is one parameter of direct and observable influence upon streambank stability for the Willamette River and its tributaries. Both the absolute magnitude of velocity and the distribution of the velocity at each cross section of the river are important, including local concentrations of high-velocity flow.

Water velocity is particularly significant because of the shear stresses produced by the flow at the solid channel boundaries. The shear stress produced within the flow is proportional to the rate of change of velocity over some distance--this describes the velocity gradient. Because the velocity gradients are normally largest at the boundaries, large shear stresses are to be expected there. If a local

concentration of high-velocity flow occurs near a boundary, that local boundary will be subject to particularly large shear stresses. This circumstance routinely occurs at the concave banks of river bends.

Velocities in the Willamette River and principal tributaries exhibit a wide range of values, both with respect to time and to location in the cross section. Local velocities during large floods may approach 18 feet per second near the concave bank (e.g., near Harrisburg, based on extrapolation of velocities reaching 14 feet per second during smaller floods). During large discharges that remain within the banks, velocities of 10 feet per second are common. At summer discharge conditions, velocities are smaller and even sluggish flows occur in many reaches of these rivers. Therefore, in terms of average boundary shear stress alone, the largest magnitudes are to be encountered during winter high-water periods.

The main thread of flow along a channel, as shown by the zones of highest velocity in successive river cross sections, may shift in location as a function of river discharge and water surface elevation. This can place a severe shear stress at certain points along the solid boundary at times when the general average shear stress is not at its largest magnitude. For example, at the straight reach known as a "crossing" connecting two curves of opposite direction, the shear stress at the bed and base of the bank may be less during periods of large discharge than during low and moderate discharges. A different situation occurs at river bends. There, the peak highwater flows commonly spread across the point bar at the convex side of the channel. As discharges

diminish, after passage of the peak discharge, the main thread of flow shifts back toward the concave side of the channel. If bedload transport has been substantial, the receding flows may lead to sufficient deposition at the outside of the point bar so as to crowd the flow against the concave bank and greatly increase the shear stresses there. Such crowding of the flow, either by the natural process just described or by the man-caused building out of a berm to protect work on a point bar, can lead to disturbance of the base of the concave bank and to its eroding into the stream.

River Discharge and Stage

The river discharge, its range and its duration are all important in establishing the velocities and shear stresses in a given channel. One way to readily summarize this information is by means of a flow duration curve showing the percentages of time that particular magnitudes of discharge are equaled or exceeded, based upon streamflow records. In an analogous manner, stage duration information can be developed to show similar data for the water surface elevation. Either of these relationships, flow or stage versus duration, is useful to determine the persistance of various flow patterns and corresponding shear stresses at or near boundaries.

The rates of change of discharge and, particularly, of stage provide other useful information on river flow and water level. Such data can be used to examine the likelihood of bank collapse resulting from large drainage forces within the void spaces of the bank.

River stage for a given discharge is either controlled by local influences at a short section of the river or by the general frictional influences over a long reach. Willamette Falls provide an example of the first type, as do severe local constrictions from the bed or banks at other places along the Willamette. These cause a backwater effect (a relative deepening of the flow, in situations found in the Willamette), for some distance upstream. This is so pronounced in the case of Willamette Falls that river stages for many miles upstream, throughout Newberg Pool, are controlled by the water level at the falls. Elsewhere, the general channel shape and roughness establish the frictional influences that control the river level from one reach to another.

Streambank Saturation Levels

The zones of saturation of soil pores in streambanks are defined by water tables or phreatic surfaces, above which only partial saturation and capillary fringes of water normally occur, except during rainy periods. Recharge of water into the streambank may result from downward infiltration and percolation of surface water, from lateral movement of ground water due to a hydraulic gradient of suitable direction, and from lateral into-the-bank movement of river water as the stream level rises.

The shape and location of the upper surface of the zone of saturation are important in assessing streambank stability. One indication of this location is the height of the seepage face above the stream level. If the two levels are moving apart over a short period of time, as when a rapid river-level drop is followed by much slower drainage of water

from the bank, this is indicative of a local increase of hydraulic gradient and seepage force in the bank. Should these become sufficiently large, local collapse of the bank can occur. As already noted, the rate of change of water level is a variable often controllable through upstream reservoir regulation. Consequently, beneficial or detrimental conditions pertaining to bank stability can be altered by such regulation once the influence of flow regulation upon bank stability has been adequately investigated.

Channel Capacity

The range of discharge is large in the Willamette Basin, with bankfull flows on the order of 20 times greater than natural low flows and with extreme floods on the order of 100 times greater than natural low flows. The channel capacity to handle such a range of discharge varies with reach of the river.

The lower Willamette, downstream of RM 50 to Willamette Falls, is entrenched between high banks in many locations so that most discharges are carried within banks. The energy gradient and average velocity increase during large discharges, as do the depth and cross-sectional area of the flow (Willamette Falls influences the water surface profile). The river curves are gradual in this reach and point bar buildup at the insides of bends is limited because of the confined flows.

Upstream of Newberg (RM 50) on the Willamette River and in the lower reaches of the major tributaries, the river channels are not entrenched between high banks except locally. Instead, one or both banks

are commonly low such that large flows can readily spread out across the adjacent land when channel capacity is exceeded. At river bends this first occurs within the highwater channel, which is principally distinguished from the low-water channel by a point bar along the convex bank. Large discharges spread over the point bar and the main thread of flow shifts away from the concave bank. In effect, the flow occurs with less curvature at such periods in a somewhat more direct down-valley direction.

Overtopping of the banks also is common. The broad floodplain serves various roles. First, the floodplain acts as a storage zone to temporarily hold excess water that cannot flow within the channel banks due to the high water level but that will later drain back into the channel. This has an effect upon the natural flow duration curve analogous to that of reservoir regulation for flood control. Second, the floodplain provides a low velocity flowage in the down-valley direction across the intervening land between successive meanders which helps relieve the main channel. For example, if the concave bank is low and water moves either onto the floodplain or into the channel, this would help in keeping the secondary currents at that bank from becoming as large as would be the case for a higher bank and greater flow superelevation at the same location. Third, overbank flow adds soil to the inundated floodplain in most areas (some scour occurs) due to deposition of fine-sized sediment carried in suspension by the river. Fourth, the return of overbank flow into the channel sometimes occurs at localized low spots along the banks and causes some scour there. Fifth, debris

carried by the high waters strands as it moves overbank onto the floodplain. This may cause local scour but also helps to catch other debris and form a permeable protection of sorts.

Channel capacity is also influenced by blockages sometimes caused by vegetation and debris within the channel banks. When bank caving occurs and causes large trees to fall into the channel, the trees may temporarily clog a portion of the channel near one bank, constricting the channel locally. Over time, branches will be broken off as the tree is shifted by the currents and the extent of blockage will diminish. Grounded snags and logs can have similar effects on a much smaller scale.

RIVER SEDIMENT TRANSPORT

Sediment is transported by rivers in two different modes: as bed load or as suspended load. Particles carried in suspension by the turbulent mixing of the streamflow are much smaller in size than those that drag, roll or bounce along the stream bottom as bed load. Silt and clay sizes (both smaller than 0.064 millimeters) are carried in suspension except in quiet sloughs and backwaters along the river where sedimentation is enhanced and the material may deposit on the bottom. Gravel, cobbles and boulders (all larger than 2mm) are sufficiently heavy that suspension is rare. Hence, particles of these size classes are moved as bed load in the Willamette and its principal tributaries. Sands, having sizes between limits of 0.064 mm and 2 mm, are most usually carried as bed load. If locally carried into suspension, such as in short high-velocity reaches of the river during periods of storm

runoff, they will return to the bed load mode of transport as soon as less turbulent waters are encountered where the large settling velocities of the sand will cause them to be removed from suspension.

The origin of the sediment immediately prior to its transport in the river at any given time offers a second means of classifying sediment transport: as bed-material load and as wash load. Bed-material load is the sediment load carried by the stream, either as bed load or as suspended load, made up of particles that originate from the bed material of the river. The bed of the Willamette is predominantly coarse but voids between these larger particles may be filled with "fines" (silt and clay sizes). These fines will be transported in suspension when the bed is disturbed, together with sand grains in some reaches of the river. Wash load is definable as that sediment carried in a stream which is not found in significant amounts as part of the bed material. Generally the wash load is taken to be the fine-sized sediment (silt and clay) that originates from and is eroded from the watershed or river banks and which is readily carried in suspension so that it "washes" through the river system without depositing.

No measurements of total sediment transport have been made in the Willamette River or its principal tributaries. Rules of thumb are often cited elsewhere which suggest that perhaps 80 to 90 percent of an alluvial river's sediment load is carried in suspension. This is subject to many conditions and assumptions. Bed load transport takes place in accordance with physical principles such that a relationship among river discharge and other hydraulic and sediment variables can be used to

predict the rate of bed load transport. In the case of wash load, there are no physical laws governing the load carried. Instead, the amount of wash load that a river can carry is only limited by that amount which is available to be carried. Therefore, the abundance of available material sets the limit upon the amount of wash load in the stream.

The transport of sediment as described above can be stated in terms of a so-called "double condition": the sediment transport in a river depends both upon the availability of the sediment for transport and the ability of the river to transport that sediment which is available; if both of these conditions are satisfied, the river will transport sediment at capacity.

In the Willamette River and the lower reaches of its principal tributaries, there is generally an adequate availability of bed material in the alluvial channels to generally satisfy the first condition. Bed material transport is thus determined by hydraulic conditions and is not limited by availability. Conversely, the river is able to carry all of the wash load that is available for transport and could carry even greater amounts. Wash load is thus limited by the availability of fine-sized sediment.

As a consequence of this, bank erosion that occurs does not choke the river with wash load but instead causes increases in suspended sediment concentrations. However, bank caving that adds coarse sediment to the river adds to the already satisfied availability of bed material. Consequently a local increase in transport ability may be needed (e.g.,

a period of larger discharge) before the freshly added material is carried farther into the system.

The transport of bed material in the Willamette River and its tributaries is a three-dimensional phenomenon, with variability in all directions. For example, at some discharges point bars or alternate bars are not disturbed whereas immediately alongside there is active bed load transport. Similarly, deposition at the edge of a point bar often occurs simultaneously with scour at the opposite side of the channel near the concave bank. There are many local sources and sinks for bed load which contribute to this variability of transport conditions. The river channel configurations and velocity patterns result in variable shear stress along the boundary. This, in turn, leads to different size distributions for bed material found along the boundary. Wherever the shear stresses are large, the smaller-sized particles that are exposed to the scouring flows cannot remain stable and are transported, resulting in coarser bed material. In such locations a surface armor layer, coarser than that beneath, is typically encountered. Wherever the shear stresses are small the smaller-sized particles can deposit and remain in place, resulting in finer-sized bed material. If a progressive rather than abrupt transition of shear stress magnitude occurs along the bed, either laterally or longitudinally or both, then a corresponding variation of bed material size can be expected.

RIVERBANK CHARACTERISTICS

The main-stem Willamette River and the lower reaches of the McKenzie, Santiam and Long Tom Rivers flow through a low-lying geomorphic

unit of frequently-flooded lands. This floodplain drops farther below the very flat valley floor terrace as the Willamette flows northward. South of Salem the Willamette River and adjacent low lands are generally incised less than 25 feet below the general level of the valley floor whereas the incision becomes much greater north of Salem, reaching almost 120 feet near Canby (1). Stream-cut terraces border the many tributaries that carry drainage from valley floor lands down to the Willamette (2). The low floodplain represents the meander belt of the Willamette River over recent centuries. It is nearly four miles wide in some places but narrows to less than a mile in width downstream from Newberg to Willamette Falls, where the incision of the river into the valley floor is greatest.

Adjacent to the low floodplain on both sides of the Willamette (and its tributaries) is a somewhat higher geomorphic unit of infrequently flooded lands. The soils are older (500 or more years of age) and have better developed profiles.

These low and high floodplain units are in turn bordered by higher, older geomorphic units that generally represent either the old valley floor terrace of the Willamette or the stream-cut terraces dropping from this higher surface. Scattered rocky hills interrupt and rise above the

---

1 Balster, C. A. and R. B. Parsons, Geomorphology and Soils, Willamette Valley, Oregon, Special Report 265, Agric. Exp. Sta., Oregon State University, Corvallis, November 1968, 31 pp.

2 Oregon State Water Resources Board, Oregon's Long Range Requirements for Water; Appendix I-2; General Soil Map Report with Irrigable Areas, Willamette Drainage Basin, Salem, 1969, 131 pp.

old valley floor. Past uplifting of the deep bedrock floor of the valley has exposed bedrock in the vicinity of Willamette Falls. Aside from these and other bedrock exposures along the valley margins, most of the valley consists of alluvium deposited in strata representing several geologic eras. This alluvium has a thickness below the present valley floor of perhaps a few hundred feet.

The present meander belt of the Willamette locally places the channel in direct contact with some of the older strata without any intervening low or high floodplains. These older strata are different in composition, compacted to a much greater degree, and generally more highly resistant to erosion than are streambanks in the recent deposits represented in the low and high floodplains. The sediments making up the floodplain deposits are generally derived from the older strata as well as from foothill and mountain sources but have been reworked through fluvial processes much more recently (on a geological timescale).

The Willamette River presently appears to be flowing in a channel that is near the upper surface of a stratum known as the Linn Gravels. This stratum reportedly varies from 20 feet to 230 feet in thickness. These gravels are exposed during summer flows at several banks where the river is in contact with this older strata. They are overlain by another old stratum (over 40,000 years old)--The Diamond Hill member--that averages three feet in thickness, is weathered, and contains sands and finer materials with a clayey texture. The Linn Gravels appear to be partially cemented and thus resistant to erosion. They often occur with a ledge or bench at the upper surface, due to greater erosion of

the less resistant formations above. The compacted and clayey Diamond Hill stratum, although thin, is also quite resistant to erosion. It, too, occurs as hardpan benches on the bank. Both it and the Linn Gravels, together known as the Rowland Formation, are inundated by high waters. Therefore, they offer a highly significant erosion-resisting formation. They can be found where the present channel is in contact with the older strata at the edge of its meander belt and are most readily seen at several locations between Harrisburg and Corvallis, with Irish Bend being the best example (3). The erosion rate at such exposed faces is slow.

The deposits above the Rowland Formation occurred in several stages to make up the thick, weakly bedded sequence of silt and associated material known as the Willamette Formation. The lower portion, referred to as the Willamette Silts, is generally thicker than the upper zone. It is overlain by a thin unit of clay up to three feet thick with a thicker silty stratum above it that is exposed as the present flat valley floor terrace. Due to the age and compaction of the Willamette Formation it, too, is relatively resistant to erosion in comparison to the present floodplain soils. This formation can be seen over the Rowland Formation at several places upstream of Corvallis as well as along a 60-foot high cutbank near RM 102 on the Willamette, near RM 15.8 on the South Santiam River, and at other locations.

---

[3] Balster, C. A. and R. B. Parsons, "Late Pleistocene Stratigraphy, Southern Willamette Valley, Oregon", Northwest Science, v. 43, No. 3, 1969, 116-129.

The lower floodplain soils are not well developed in their profile. The riverwash deposits on bars are the most recent of all deposits. These are cobbly, gravelly or sandy with much variability and stratification and with little vegetal cover other than brush. The nearby lower floodplain levels have soils that are shallow-to-deep over older riverwash deposits. These are typically sandy loams or silt loams. Such soils drain very rapidly and have low water-holding capacities. Therefore, where they occur as streambank material they can be expected to drain rapidly during floodwater recessions and to be sufficiently uncompacted and non-cohesive that erosion and bank caving from soil particle washout might be an important problem.

The higher floodplain soils are better developed in their profile. They are typically silty clay loams with variable drainage characteristics, ranging from well drained to poorly drained. Therefore, when they occur as streambank material, variable erosiveness and bank caving conditions might be expected. Their clayey development and somewhat greater age, height, and compaction should improve their resistance to scour somewhat. But their poor drainage could contribute to saturation of the banks and their caving at times of rapid flow recessions after periods of storm runoff.

V. WILLAMETTE RIVER BASIN
FIELD SITUATIONS INVOLVING NATURAL MEANS OF STREAMBANK PROTECTION

STUDY APPROACH FOR FIELD INVESTIGATION

The examination of existing field situations in the Willamette River Basin where bank shape, vegetation or riparian land use appear to have been instrumental in preventing or retarding erosion was one of the elements of this study. Work was based upon use of aerial mosaics of the Willamette River and tributaries to identify likely study sites, followed by field investigation to characterize the conditions at these sites. River locations where bank shape, vegetation or riparian land use may have aggravated bank erosion were also investigated.

For the main-stem Willamette River, comparison was made of aerial mosaics from photographs taken on 6 April 1961 and 2 May 1972, spanning an 11-year period that included an estimated 100-year flood in December 1964. The purpose of this comparison of aerial mosaics was to find locations where one might ordinarily expect bank erosion (see the following section) but where little or no erosion was indicated over the intervening period. From this review and from discussions held with technical staff members of the Portland District, U. S. Army Corps of Engineers, particular sites were chosen for field examination. The field investigation was conducted by boat and by foot to determine features of the hydraulic, soil, topographic, vegetative, and land use

conditions at each site. The factors which appeared to have led to bank stability or instability were identified and the likely influences of bank shape, vegetation and riparian land use were noted.

For the South Santiam River and the Long Tom River, similar procedures were followed except that only a single set of aerial mosaics was used in each case.

LIKELY SITUATIONS FOR BANK EROSION

Prior to field inspection it is possible to identify the likely situations where streambank erosion could be expected. Then, such situations can be sought on aerial mosaics or in the field. From this it may be noted whether or not the expected conditions exist at each location, allowing confirmation of the anticipated conditions or inferences as to the reasons for why the anticipated conditions were not found.

The basis for this potential for prediction lies in the nature of the Willamette River and the lower reaches of its tributaries. These are alluvial streams on the valley floor with very few bedrock outcroppings except in the proximity of foothills. The streams exhibit meandering and are subject to the causative forces of nature, aided or abetted by man, that produce and propagate meanders. The principal factors are the streamflow regime, the characteristics of the alluvial sediments found in the stream, in the banks and in the floodplain, the yielding boundaries of the channel, the valley and channel slopes, and the limited number of natural or man-made rigid boundaries.

The situation most likely to produce streambank erosion is a bend in the stream. Erosion generally occurs on the outside (concave) bank

at a bend along much of the length of the bend, often extending a short distance downstream. The inside (convex) bank of the bend, on the other hand, is relatively well protected from erosion and instead represents a zone of sediment accumulation and vegetation growth. Sharp bends are likely to experience more erosion at the concave bank than do gradual bends, due to more highly concentrated flows there.

Another situation likely to produce streambank erosion is a gravel bar in a channel, whether the channel is relatively straight or is curved. The bar deflects the main thread of flow away from it and toward the opposite bank, or toward both banks if the bar is near midstream. This concentrates the flow of the bank, increases the shear stresses at that boundary, and thus increases the likelihood of bank erosion.

A third situation likely to produce streambank erosion is an irregular bank line resulting from locally resistant bank material, locally protruding vegetation, irregularly dumped material, or similar causes. Such irregularities jutting out into the flow act as sources of eddies and locally stronger turbulence which can direct scouring currents against the banks just downstream.

These three situations -- bends, channel bars, and irregular bank lines -- provide important leads to the finding of streambanks where erosion can be anticipated. Aerial mosaics provide a rapid means of scanning a river reach to identify such situations and potential erosion sites. Evidence that erosion is, in fact, taking place at these sites may be found from the aerial mosaics in the form of bare,

new-looking gravel bars or steep concave banks, the two often being closely associated. Absence of these signs suggests that erosion is not active at a site. Tentative confirmation of these preliminary findings can be obtained by comparison of aerial mosaics spanning a period of one or more years. The scale at which the aerial mosaics are printed is important in this step, as bank erosion rates are likely to be on the order of 5 to 50 feet per year in cases of moderate to severe erosion (except where a severe change of channel location occurs, which may involve much greater distances).

Confirmation of these preliminary findings requires field examination. At this time, additional river locations can be examined for which assessments of bank stability could not be readily made from aerial mosaics. Field study also provides the opportunity to identify the causative factors for bank stability or instability. In particular, with respect to the reported study, the likely influences of bank shape, vegetation and riparian land use on bank stability can best be identified in the field rather than from aerial mosaics.

SELECTED SITES

The described study approach was used to seek out field sites along the Willamette River upstream of the Newberg Pool at River Mile (RM) 50 to Eugene (RM 180). The approach was also used for the South Santiam River from Foster Dam (RM 37.5) downstream to its junction with the North Santiam River.

Similar use of aerial mosaics was also made for the Long Tom River from Fern Ridge Dam (Station 0 feet) downstream to its junction with the

Willamette River (Station 1250+00 feet). In this case, however, long reaches of this river were examined in the field, rather than restricting field investigation to a smaller number of specific sites.

The selected river sites and reaches studied are described in the following sections.

THE WILLAMETTE RIVER

Between the upper end of Newberg Pool (approximately RM 50) and Eugene (RM 180) occur a very large number of river bends, channel bars and irregular bank lines. Because some channel disturbances may have been caused by recently discontinued sand-and-gravel removal operations, the river reaches near cities such as Harrisburg, Corvallis, Albany and Salem were omitted from field investigation.

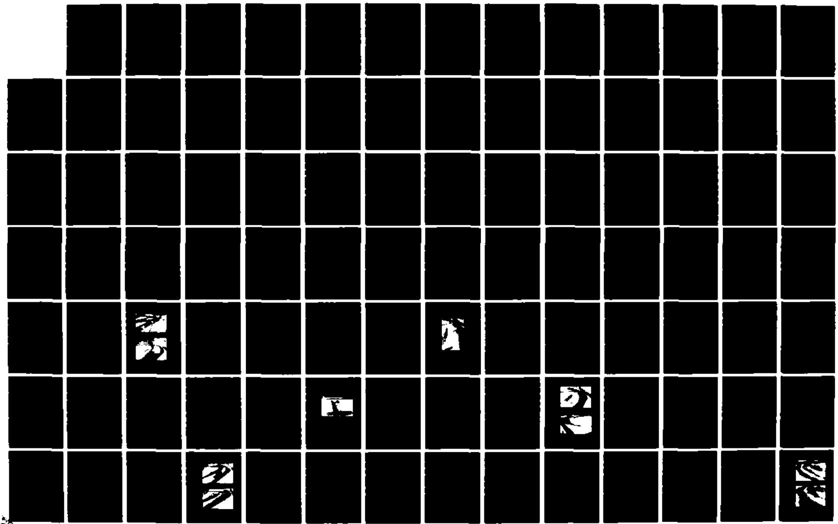
Upstream of Corvallis, the aerial mosaics indicate that channel changes are quite common. Changes at a given location would in many cases cause changes in the flow alinements downstream to induce changes there also. In several cases the land adjacent to eroding concave banks is cleared of most trees to allow cultivation. However, many other eroding concave banks have a fringe zone of trees and other vegetation. Channel bars are often identifiable downstream of eroding bends in the "crossings" (short reaches were the main thread of flow switches across the channel from the concave bank of the upstream curve toward the outside of the next downstream bend). Growth of channel bars has sometimes led to curve enlargement, even in nearly straight reaches downstream of the bar (e.g., upstream of Harrisburg near RM 166, as compared in the 1961 and 1972 aerial mosaics).

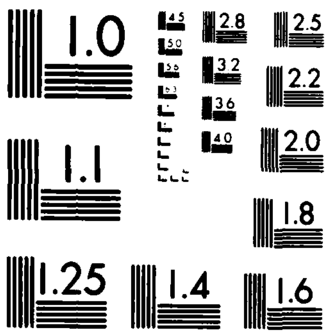
Downstream of Corvallis the aerial mosaics indicate that channel changes also occur but are not as numerous as in the reaches farther upstream. However, it is difficult to separate out the beneficial effects of past maintenance dredging (pipeline method) and snag removal in the Willamette River as far upstream as Albany and Corvallis until 1973, whereby channel gravels were often placed against the banks to improve mid-channel flow conditions. These actions tended to retard bank erosion processes. Revetments are quite common downstream of Corvallis, where more than 30 are to be found out of almost 80 along the Willamette. In past years, sand and gravel removal from the channel and from bars, particularly point bars, has been more common from Corvallis downstream. Thus, seeming stability of banks that would otherwise be likely to erode is indicated by aerial mosaics for many locations downstream of Corvallis (RM 131).

A significant change in the size of meanders is suggested downstream of Corvallis, based upon inspection of aerial mosaics. The curves tend to be longer and have larger radii. More gradual crossing-over from one bend to the next is also indicated. Channel width is also greater, of course, reflecting increasing discharges in the downstream direction. But the relative curvature of bends increases downstream of Corvallis. Small values for this ratio indicate "tight" or sharp curves and high potentials for erosion of concave banks whereas large values indicate gradual curves and reduced erosion potentials. Therefore, the aerial mosaics indicate that the erosion potential is lower downstream of Corvallis than upstream. It is perhaps significant in this regard that the

AD-A150 614 WILLAMETTE RIVER BASIN STREAMBANK STABILIZATION BY NATURAL MEANS(U) OREGON STATE UNIV CORVALLIS WATER RESOURCES RESEARCH INST P C KLINGEMAN ET AL. JUN 76 2/3

UNCLASSIFIED F/G 13/2 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

average channel slope and energy gradient (rate of energy dissipation) are less downstream than upstream of Corvallis, being about 2 feet/mile from Newberg to Corvallis, about 3 feet/mile from Corvallis to Harrisburg and about 4 feet/mile from there to Eugene. Locally steeper and flatter reaches occur.

The locations selected for particular field investigation are identified here by river mile (RM) and, in some instances, by the name of nearby features. The locations include:

RM 89-90	Hayden Island; Doves Bar
RM 92	Budds Chute; Budds Island
RM 93.5	East Independence
RM 99	Tyson Island
RM 102-103	-- (high bank)
RM 105-106.5	Wells Island
RM 108-109	Santiam Bar
RM 137-138	--
RM 140-141.5	--

A discussion of the relevant aspects of bank stability and the likely governing factors is given separately for each field location.

<u>RM 89-90</u>

The Willamette River between RM 89 and RM 91 includes an upstream straight reach leading into a gradual curve to the right, with a relative bend curvature of about 6, followed by a comparatively straight reach with a slight tendency to curve to the left. Downstream of RM 89

a sharp curve to the left occurs (relative bend curvature of about 3) and a revetment on the concave bank between RM 89.3 and RM 88.4. Aerial mosaics and conversations with Corps of Engineers representatives indicated that erosion is occurring along the left (west) bank of the river opposite Doves Bar (RM 89.5 to RM 89.9), where dredge spoils had formerly been placed. The cause of erosion appears to be the gradual growth of the long-radius bend. However, when observed during a period of moderately high water the river flow was well distributed across the channel as it left this bend and no erosion was evident downstream of RM 89.5. It was not possible to obtain a good view of conditions farther upstream to check on erosion problems there. Aerial mosaics indicate that erosion is not occurring rapidly. Bank soils are of the low-floodplain type and erodible. The large relative bend curvature and the smooth bank lines favor gradual rather than rapid erosion at this curve because of well-distributed currents and lack of features that crowd the flow against the banks. No low-flow examination was made; however, the 1972 aerial mosaic shows a gravel bar at RM 89.4 near mid-channel. This bar would cause the low flows to be somewhat concentrated near both banks, increasing the potential for erosion there.

RM 92

Erosion is occurring along the left (west) bank of the west channel (Budds Chute) at RM 92.0 to RM 92.2, a half mile upstream of an existing revetment. At high water, most of the Willamette flows through this channel rather than through the east channel, due in part to the alinement

given the flow from upstream at the crossing between curves near RM 93.0. Budds Island, a large bar along Budds Chute, collects a considerable amount of floating debris, including tree trunks. Shallow gravel deposits appear to extend upstream from this bar. The resulting shoal area helps direct much of the streamflow into Budds Chute rather than into the eastern channel. Therefore, even though the relative bend curvature based on full channel width is very large at RM 92 (about 12 to 15), which would indicate little likelihood of erosion, the upstream end of the bar (Budds Island) serves to deflect the flow toward the west bank and concentrate it there, reinforcing a tendency developed at the crossing (RM 93). The vegetation at the west bank has had limited effect in retarding erosion. Vegetation remains at the top of this bank but the soil on the bank face is exposed to the flow because of erosion. Soils are of the low-floodplain type and erodible.

RM 93.5

The information available from Corps of Engineers representatives suggested that erosion of the concave right (southeast) bank near RM 93.5 was arrested after the removal of gravel from the point bar opposite that bank. The 1972 aerial mosaic shows that a sizeable scalping operation had been undertaken at the point bar. The river bend from RM 93 to RM 94 is not a fully developed meander, as it impinges against foothills near the lower end of the bend. Through the upper half of the bend, including the erosion zone, the relative bend curvature prior to point bar removal was about 4. The relative bend curvature for large

discharges has been increased to 5 by removal of the point bar. With the bar removed, high waters place less stress against the concave bank due to the much greater ease of flow across the zone of the point bar, which is completely inundated. The waterway is quite wide as a result; the current against the concave bank is still strong but is not excessive and not as great as formerly. Another factor which may help keep the rate of erosion low at the concave bank is that the bank is not very high and can be inundated by floodwaters. This inundation will alter flow directions and should reduce the shear stress compared to a "bank-full" condition there. Local soils are of the low-floodplain type and erodible.

RM 99

Bank erosion is slowly occurring at the left (south) bank of the river opposite the land identified as Tyson Island, at RM 99. The eroding bank is at the outside of a gradual right-hand curve with a relative bend curvature of about 10. Formerly, dredge spoils were placed against this bank, according to Corps of Engineers representatives. A gradual left-hand curve upstream at RM 100 places the crossing between bends at approximately RM 99.3. Downstream, at RM 98.7, an unstable wide channel zone with mid-channel bars occurs and extends to RM 98, along Murphy bar. A point bar exists on the opposite bank, attached to Tyson Island. Some growth of this point bar is indicated and vegetation on the bar is becoming quite well established down to the water line at moderately high flows. Higher flows than observed may be directed more

strongly toward the eroding left bank. The eroding bank has an irregular shape, due to clumps of vegetation, including short trees, and to dumped material, including wire mesh, that has been added to help stabilize the bank. The bank slope is roughly 2H:1V (two feet horizontally for each foot of vertical rise). At the observed moderately high flow, the water deflects from these protruding irregularities and forms a wake of eddies slightly obliquely to the bank. At very high flows these protrusions would have less effect in deflecting the flow because they would be nearly submerged. A short distance downstream the landowner has also placed tree trunks along low-lying banks to reduce the velocities of runoff from fields and from flood flows that overtop the banks. The landowner indicated that erosion seems to have become worse since the cessation of channel dredging and spoil disposal along the banks. As at downstream study sites, streambank soils are of the low-floodplain type and erodible.

RM 102-103

The reach from RM 102 to RM 103 has a dramatic, nearly vertical 60-foot high concave east bank against the old valley floor terrace where erosion appears to be happening only slowly, leaving the bank more stable than one would expect on first examination. Exposed strata are from the Willamette Formation and, possibly, the Rowland Formation. The river approaches RM 103 adjacent to low-floodplain soils and makes a gradual left-hand band after a crossing at low land that forms a high-water mid-channel bar opposite Whitman Bar. This bend from RM 102.6 to

RM 103.2 has a relative bend curvature of about 5 or 6, not sharp enough to indicate a severe erosion potential due to flow crowding the outside bank nor gradual enough to indicate a minimal erosion potential. The constricted crossing at RM 103.4 was not accessible for examination by land, but aerial mosaics suggest there is some erosion of both banks of the main channel there. Dredge spoils had previously been placed along the right bank, according to Corps of Engineers representatives. The flow alinement from this crossing into the downstream bend is smooth and gradual, which promotes stability of the concave bank.

The high bank is bare of vegetation along the exposed face but has trees and other growth at the top of the bank and has some growth along the base of the bank. Here, bank failures on the face have left an accumulation of earth at the toe that offers protection in two ways: by keeping the flow away from the bottom of the vertical bank and by allowing vegetation to become established and help maintain the toe material in place. A point bar at RM 102.7 to RM 103.0 on the left (northwest) bank opposite part of the high bank does not appear to have grown in recent years, although it has a heavy cover of vegetation. Growth of this point bar would appear to depend upon future changes at the upstream crossing. Downstream from RM 102.6, the bend curvature becomes much more gradual (the relative bend curvature is 11 or 12) and the larger toe deposits at the concave bank contain trees as well as smaller vegetative growth.

The Willamette Formation soils at the concave bank from RM 102 to RM 103 are of great importance in retarding the rate of bank erosion.

The banks stand nearly vertically in many places and fail by the shearing off of large blocks of soil, as evidenced by cracks at the top of the bank, these dropping to the base of the bank where they form a deposit consisting of smaller blocks of soil rather than a loose, crumbly deposit. The bank contains distinct hardpan strata. For example, a "hard-point" with a hardpan stratum on the right bank at RM 102.0 extends out into the channel and acts as a turning point, downstream of which the river sharpens its left-hand curvature. Also, a tributary creek enters the Willamette through the concave bank at RM 102.5, having cut downward through the bank material over a length of about 800 feet in a series of rapids followed by small waterfalls, the latter being 10 to 20 feet in height and denoting the surfaces of the hardpan layers. Plunge pools and banks eroded by the resulting eddies are to be found where the falls have slowly cut their way upstream.

From RM 102.0 downstream to RM 101.7 the river makes a sharper turn to the left, the relative bend curvature increasing to about 3. The flow is crowded against the outside bank, which at RM 101.9 is a flood-plain terrace about 10 feet above moderate high water and extends out as a foreground deposit a few hundred feet wide in front of the high bank that continues from upstream and marks a long-abandoned location of the river. The terrace begins between RM 101.9 and RM 102.0 and has a heavy vegetative cover there due to the protection from flows offered by the sizeable hardpan outcropping at RM 102.0. At RM 101.9 a creek cuts across the terrace. From RM 101.9 downstream along the remainder of this short sharp curve the terrace bank is eroding and is bare of

vegetation on its face. The short dense vegetation on the top of the terrace bank offers no protection from river currents but has prevented surface runoff from cutting the top of the bank. The bank is not high enough to provide much soil as temporary toe protection when bank caving occurs, unlike the high bank upstream.

RM 105 - 106.5

The Willamette River divides around Wells Island between RM 106.5 and RM 105. Aerial mosaics and information from the Corps of Engineers representatives indicate that this reach has been relatively stable except for slow erosion on the right (east) bank of the right (east) channel along Wells Island. The observed moderately high flow divides about Wells Island roughly equally or with slightly more flow in the east channel. The upper end of the island causes the east channel flow to turn to the right. Some erosion may be occurring at that part of Wells Island, although at high water a heavy vegetative cover, including young willows, is all that is visible. Dredge spoils had previously been placed in this area. The east bank of the east channel, a low floodplain, has trees and smaller vegetation. It appears to be resisting erosion except near RM 105.5, where the flow turns back to the left near the lower end of Wells Island and crowding of the bank by the currents has caused scour there.

RM 108 - 109

The smooth curve of the Willamette River between RM 108 and RM 109 has experienced erosion of the east bank just upstream of the mouth of

the Santiam River. The relative bend curvature from RM 108.4 to 109.1 is about 4 to 5 before a short transition into a reverse curve of larger relative bend curvature downstream of RM 108.3. Until 1973, dredge spoils were periodically placed along the concave banks here to retard erosion. Since then, erosion of the right bank has resulted in the placement of a private revetment along part of that bank (approximately from RM 108.3 to 108.7). However, vegetative growth on the opposite point bar maintains strong highwater flows near the outside bank, rather than providing a greatly expanded waterway across the point bar at such flows. Consequently, slow erosion is continuing upstream of the revetment adjacent to low-floodplain lands.

RM 137 - 138

After a short right-hand curve upstream near RM 138.3, the Willamette River makes a very gradual left-hand curve between RM 137.0 and 138.0, the relative bend curvature being about 12. Coming out of the upstream right-hand curve, the flow has produced a point bar extension on the right (east) side of the channel at RM 138.15. Some water flows behind the point bar extension because of an earlier channel configuration that has not yet been completely obliterated. The upstream flow alinement and this point bar growth have led to erosion of the west bank just opposite and downstream from the bar where the channel was formerly straight but now causes the west bank to become the concave bank. Now, only a very short crossing exists near RM 138.0.

The current is well distributed across the channel throughout the reach from RM 138 down to RM 137, being only slightly stronger on the right half. Vegetation is abundant along both banks but has been subject to scouring flows, mainly during the larger discharges because the banks confine the high waters.

The principal erosion on the left bank has been between RM 137.9 and RM 138.1. Here, the bank face is of moderate height and soils are exposed in most places. The likely cause for this relatively recent erosion is the deflection of large flows toward that bank by the upstream curve and recently growing point bar on the east side of the river at RM 138.15. The erosion of the low floodplain soils is only progressing slowly. Trees eroded from the bank have washed downstream along the left bank as far as RM 137.7.

Along the right bank there is no single zone of concentrated erosion. Instead, the bank shows signs of scour between trees that grow low on the bank and these trees have exposed roots. The tree roots have been important in maintaining bank stability, as the bank line elsewhere is set back from the tree line. Most likely, the trees play a dual role regarding bank erosion: (1) tree root support helps maintain the bank line rather than permitting its eastward erosion; and (2) at higher flows, the tree trunks and root clumps generate eddies that swirl against the downstream bank, between trees, and cause local scour. The bank soils appear to belong to the Willamette Formation and probably are underlain by semi-cemented gravels (not visible).

At RM 137.5 a resistant point on the right bank, covered mainly by grass, juts out into the flow. It deflects the flow from the bank, causing a line of turbulent eddies that move away from that bank and a reverse current that swings against that bank just downstream. At larger flows than observed, it is apparent that this eddy current is strong enough to cause some scour at the right bank.

Downstream of RM 137 the east bank is scoured but is not eroding noticeably. The top of the bank has only short vegetation and cultivated fields. The bank material is a higher-floodplain soil (different from that upstream of RM 137) over a hardpan that includes semi-cemented gravels and provides toe protection. Perhaps of comparable significance to the stability of this bank is the abrupt widening of the river toward the west, where continued erosion of the left bank led to the construction of the Danis revetment in 1974.

RM 140 - 141.5

Downstream from its confluence with the Albany Channel at RM 141.6, the Willamette flows along a relatively straight channel to RM 140.3, with flows well distributed across the channel. Heavy vegetation including brush and trees lines most of both banks. The soils at the left bank are in the low-floodplain category while those at the right bank are from the old Willamette Formation, underlain by the Rowland Formation. Local scour has occurred at two zones along the left bank. One of

these extends upstream from RM 141.0, with limited scour extending along that bank at several locations for distances of up to 100 feet or more. Between these eroded stretches, wild blackberries and other dense brush still protect the bank. Another zone of erosion along the left bank is just downstream of the entrance to Clark Slough, at RM 140.7, for about 0.1 mile. Flow into this slough (eventually leading to the Booneville Channel) apparently has locally drawn the river current more closely and strongly toward the left bank in this zone.

At RM 140.2 the Middle Channel begins. It follows the generally straight alinement from upstream while the Willamette turns to the right. High water overflows the upstream end of Bear Island here, depositing gravel and stranding debris. Simultaneously, the rightward-turning flow has in recent years began to develop a concave-bank erosion at RM 140.1 to RM 140.0 along the east edge of Bear Island.

Vegetation on the point bar at the right bank near RM 140 is flourishing and small willows are well established almost to the water line at moderate flows. This prevents flood flows from cutting across the point bar in any large measure and maintains pressure against the concave left bank opposite the bar at such times.

THE SOUTH SANTIAM RIVER

The South Santiam River meanders extensively throughout the 37.5 miles from Foster Dam to the confluence with the North Santiam River. From aerial mosaics, the channel of the South Santiam appears to be most consistent in its location upstream from RM 18, where only the reaches near RM 24 and 28.5 show signs of recent large shifts of channel location.

Downstream from RM 15, the channel shows many signs of active erosion and channel shifting. Twenty two revetments have been constructed in the lower 15 miles of the river compared to four revetments in the upstream 19 miles.

Rock outcroppings at the river bed and banks exert a strong influence over channel stability at many places upstream from RM 18 to Foster Dam, even though the channel meanders through alluvial deposits over most of this reach. Local steep channel gradients and even stretches of white water rapids occur.

A shorter reach in the upper half of the South Santiam was examined in detail, this being the river from RM 28 downstream past RM 26. Particular interest focused on the bend at RM 26, for which the aerial mosaics indicate a relative bend curvature of less than 4 and a vegetated concave bank that should be susceptible to erosion but does not indicate signs of erosion. Field examination showed that this short reach has extensive local bedrock outcroppings. At RM 26, bedrock outcrops low on the concave bank and along part of the nearby streambed, providing the stabilizing condition for that bend. Vegetation flourishes on both banks and on local gravel bars, extending nearly to the low water line in many areas. This vegetation includes grass, bushes and trees. The vegetation along the concave bank at RM 26 apparently hides the bedrock from aerial view. An irrigation intake on the flat convex bank at this bend, with exposed soil adjacent to it, is well situated and protected because of the stable configuration of both banks and the weak currents near the submerged suction line.

Downstream from RM 18 bedrock outcroppings are not evident. The river has a flatter gradient with fewer rapids and with stretches of deeper, slower-moving flows.

The channel near RM 15.8 was chosen for detailed examination because the river makes a sharp left-hand turn there and the concave bank appears to be quite stable. From aerial mosaics the relative bend curvature is about 3, sharp enough for bank erosion to be quite likely. However, close inspection showed that erosion was not a problem. The flow turns to the left against a concave bank approximately 40 feet high. The eroded soil covering much of this bank is a crumbly gray loam. The bluff itself consists of the resistant Willamette Formation. It is heavily vegetated with large fir trees and various types of smaller brush. The bank is quite steep, with a slope of approximately 1H:4V. However, a broad toe of soil and vegetation at the base of the bank offers protection against scouring flows. A flat mid-stream gravel bar just upstream of the bluff splits the low flows and causes a swift current near the base of the bluff. Larger discharges inundate this bar and the point bar at the convex bank opposite the bluff, increasing the relative bend curvature slightly. A small creek that carries winter drainage joins the South Santiam at the base of the bluff in a protected area to the upstream side of the zone where the river impinges against the bluff. Broken concrete slabs and rubble have been dumped on the bank near the creek to protect against scour. The erodibility of the bluff soil is indicated by this need for protection. Therefore, it is believed that the bluff is principally protected from the South Santiam

River flows by means of the broad, vegetated toe at its base and because the flat channel bar and point bar opposite the bluff can be easily inundated by higher discharges to provide an expanded waterway and thus relieve the flow pressure against the base of the bluff.

THE LONG TOM RIVER

General Observations

In distinct contrast to the natural meandering of the Willamette and South Santiam Rivers, the Long Tom River downstream of Fern Ridge Dam (RM 25.7, Station 0+00 feet) is very much a realined and revetted river. It is also considerably smaller, being approximately 100 feet wide over much of its length in contrast to 200-300 feet for the South Santiam River and 300-600 feet for the Willamette River the selected study reaches.

To provide a channel for efficiently evacuating stored flood waters from Fern Ridge Reservoir between winter storms, much straightening of the former meandering alluvial river has been undertaken, dating back to completion of the dam in 1941. Revetments are almost continuous on both banks from the dam (Station 0+00) downstream past Smithfield (Meadow View) Road to Station 169+10 and from Station 245+80 to Station 479+20. Other revetments occur at bends and at other locations where erosion threatens. Along other banks and between riprap revetments in the above-mentioned reaches, earth embankments protected by planted and natural vegetation help maintain the channel alinement. The embankments generally appear to have slopes of 2H:1V.

The streambed of the upper two-thirds of the Long Tom River below Fern Ridge Dam is maintained at a flat gradient by means of five bed stabilizing structures (stone sills across the stream) and three larger drop structures. These locally dissipate excess river energy and allow flatter-gradient flows of lower velocity between them than would otherwise be the case. This reduces the boundary shear stresses compared to those that would have occurred without such structures in the realined channel.

The resulting low-flow channel gradients are flat for most of the river below Fern Ridge Dam. Small riffles occur in straight reaches. These are associated with "crossings" of the internal low-flow meandering pattern between low gravel bars. Shoals also occur in crossings between closely placed bends of the river. There seem to be more riffles downstream of Monroe than upstream. Between riffles in both reaches the low-flow velocities are quite small. A long slack-water stretch occurs in the downstream reach, approximately between Stations 1067+00 and 1132+00, which is controlled farther downstream by alternating channel bars and riffles. Except at riffles in both reaches, the general velocity is less than 1 foot per second at the low flows observed.

The streambed contains a broad range of material varying from cobbles and gravel down to smaller particles. Cobbles of several inches diameter are evident at riffles. These may have been part of the stone revetments at one time. River gravel of 1 to 2 inch median diameter is common on the bars.

The high-water channel appears to be generally wider downstream of Monroe than upstream. This leads to differences in channel features between the embankments. In the upstream reach, the channel is trapezoidal. Low point bars are found at the insides of bends and low alternate bars occur in straight reaches, all adjacent to the sloping embankments. Similar bars occur in the downstream reach, but an intermediate-elevation foreground in many places exists between the low-water channel and the higher embankments, almost forming a trapezoidal channel within a trapezoidal channel. Exposed hardpan or semi-cemented gravels are commonly visible at the edges of the low-flow channel in the downstream reach. Perhaps the embankments were set back on this hardpan to allow for some long-term erosion or to handle larger flood flows from local runoff.

Vegetation is abundant on the banks. It is also quite varied; including grasses, weeds, poison oak, blackberries and black raspberries, other berry shrubs and brush. Trees overhang the water at some points, occasionally with their roots exposed along the banks.

The man-made embankments of the Long Tom are in some places higher than adjacent lands. Local drainage behind the embankments is often guided to small creeks which then enter the Long Tom from culverts at intermediate levels through the embankments. Additional revetting for erosion protection has been added at many such culverts.

Smithfield Road to Siuslaw Highway

The reach of the Long Tom River from near Smithfield (Meadow View) Road downstream to the Siuslaw Highway (Cheshire Road) was inspected on

several occasions between stations 185+00 and 317+00 for a distance of 13,200 feet. Streamflows at the times of field inspection, as measured farther downstream at the Monroe gaging station, ranged from a low of 40 cubic feet per second (cfs) to a high of 5040 cfs during peak runoff.

Bank revetments at many locations on both banks of this reach protect about two-thirds of the reach. The revetments do not extend to the top of the banks in most places, covering approximately the lower two-thirds of the bank. Vegetation or occasional exposed soil can be found above the top of the riprap revetments. At the large observed discharge (5000 cfs at Monroe), consisting mainly of local inflow from downstream of Fern Ridge Dam, water depths were less than one-half to two-thirds of bank height in this reach. Hence, the combination of stone and vegetal bank protection appears to be quite adequate for the normal range of channel flows. Because of upstream flood regulation, it is likely that the vegetation above the low-level revetments is only infrequently inundated.

In structural condition, the toes of the revetments appear to be bulkier in thickness and hence better protected than the riprap rock above. However, the ends of revetments do not appear to be keyed into the bank; rather, they just end without any added protection being evident. Instead of being flush, many rocks protrude from the revetment surfaces. Scour and other disturbances have caused many riprap stones to fall into the channel. There, they either have been left near the base of the revetment or have been carried away for some distance by the current. As a related problem, protruding riprap rock, such as that on

the right bank in the relatively straight reach upstream of Station 188+75, can force the high-water flows more strongly against the opposite bank and cause local scour there. Other types of local failures of revetments are evident, such as a slumping of the right bank near Station 169+10. (The cause of this failure is unknown. Blackberry bushes grow on the opposite bank but the thread of flow appears to be in the center of the stream. Therefore, either an ordinary slope failure or deflected currents acting at the toe of the bank may be involved.)

Nearly all concave banks of bends in this reach of the Long Tom have been revetted, either continuously or intermittently. An exception is the concave bank near Station 200+00. Here, a rocky hill is close to the left bank (the outside of the curve). Approaching the curve, this bank is tree-lined and brushy. Basaltic rock is exposed at this concave bend. Together, the vegetation and rock outcropping offer sufficient protection to the bank so that no additional protection is needed.

Relatively straight reaches and the convex banks of curves are also revetted many places in this reach. At some sites this was apparently done to dike low-lying land near the channel and thus increase the channel capacity for releasing stored flood waters from Fern Ridge Reservoir.

During periods of substantial local runoff, flows from culverts can exert an important influence upon river currents and bank scour.

For example, large local flows from a culvert on the right bank just below the Smithfield Road bridge were observed to deflect the current into the left bank of an angle of nearly 80 degrees to the channel axis. Farther downstream, other culvert discharges only affected the river flows over half or less of the width of the channel and did not cause significant crowding of the flow against the opposite bank or noticeable scour there.

An exception is found near Station 188+75. As already noted, protruding riprap on the right bank upstream of the culvert causes the flow to disturb the left bank during high waters when the channel is about two-thirds full. Lower on the right bank, just downstream from Station 188+75, a zone of erosion was noted that apparently was caused by eddies from the interaction of culvert and river flows due to the culvert discharging from the right bank. Apparently the flow then "bounced" across to the left bank farther downstream, where scour was also noted. Hence, bank scour near Station 188+75 may be attributed to a combination of the protruding riprap and the culvert discharges.

At some locations, such as Station 240+00, the discharge from culverts and the disturbance of local river currents caused by the protective riprap near the culvert exit appear to cause eddies that attack and scour the bank just downstream of and on the same river bank as the culvert. In line with the upstream edge of the culvert, the protective riprap appears to have been dumped randomly and extends well out into the low-flow channel.

Somewhat related to scour caused by culverts is the flow disturbance caused at some sites where irrigation water is pumping from the river in the summer. Some farmers have built up small gravel bars around the sumps where suction lines are placed to pump water from the river. A minor amount of local scour appears to have been caused at adjacent banks in the past when winter flows increased in depth and velocity and eddies formed at these bars.

Very little or no erosion was evident at many unrevetted zones. The stability of these banks could be attributed to such factors as straight channel alinements, straight flows well distributed across the channel with the main thread of flow in mid-channel away from the banks, the absence of bars in the channel, and the presence of dense vegetative covers of grass and small brush on the banks.

Gravel bars in the channel cause problems at some locations. For instance, a gravel bar on the left bank downstream of the convex left bank of a minor bend near Station 178+25 appears to have aided in forcing the river flow against the right bank at a location where the channel is straight. There, undercutting and bank failure have resulted. At a different location, near Station 215+00, a bar occurs in mid-channel, well covered by grass and small brush. The smaller flows are forced around this bar and against the adjacent banks, but a strong vegetative cover protects the full slope there so that no scour is evident at or above the toes of the side slopes. This location has the potential for future problems if either the bar or its vegetative cover grow very much.

The vegetation appears to have mixed success in controlling erosion. The severity of scouring currents appears to be a controlling factor in this effectiveness. For instance, where revetments have been required due to large velocities at concave bends, vegetation might not have been highly effective because of difficulties in getting it established and maintaining it. But there are examples of success. For instance, between intermittent revetments on the concave bank near Station 177+25 a grass cover has been quite adequate to protect the embankment, even though the relative bend curvature is only 3 or 4. Areas densely covered by berry vines are also well protected, even though scour occurs in adjacent unprotected places on the bank. A healthy vegetative cover and root system on the banks that extends down to low water can give good protection even when vegetated channel bars or cu[illegible] at the opposite banks force the flow against these banks, as was found near Station 215+00.

Bulky, brushy vegetation appears to have a different effect on bank stability than does vegetation that can flatten down during dormant periods when large discharges occur. An excessive growth of bank vegetation can cause problems at the opposite bank while offering complete protection to the bank on which it grows. Conditions near Station 195+00 demonstrate this. Just upstream of the right-hand bend at Station 200+00 the channel describes a very gradual right hand curve. A small bar occurs adjacent to the convex right bank. Vegetation along the slightly concave left bank completely protects it. But near Station

195+00 the brush growth becomes very large on the left bank. This produces a modest narrowing of channel width. High-water flows are deflected from the brush and are crowded against the right bank opposite it. Erosion there has been severe. The eroded bank stands at a steep slope of roughly 1H:3 or 4V.

Trails used by people or animals run down the face of the bank in a few places, exposing the soil. No particular damage resulting to adjacent bank areas could be noted on the straight bank near stabilizer #4 at Station 142+00 nor at the convex bank of a gradual curve near Station 169+10. Nor does local erosion appear to have occurred because of a fishing trail leading to a gravel bar at the convex bank near Station 178+25. At these convex bends, the trails were at the downstream portions of the curve, in favorable zones of weak flow velocities near the bank during high-water flows. One shallow roadway crossing of the river in a straight reach near Station 270+00 was incorporated in revetments on both banks and thus caused no bank scour problems.

Monroe to Irish Bend Road

Inspection was also made of the reach of the Long Tom River from near the Monroe Drop Structure (Station 890+00) downstream to below Bundy Bridge at Irish Bend Road (Station 1190+00), covering a distance of 30,000 feet.

This downstream reach, although diked or leveed in many places, is characterized by relatively few revetments. Structural features of

existing revetments appear to be similar to those for the upstream reach. The few short revetments are either at concave banks of curves (with continuous or intermittent paving) or at limited zones on straighter channels. The revetments only occur on one bank (rather than both) at any given location. Not all curves are revetted, even though an embankment is present. There appears to be scour along many of the unrevetted embankments in the upstream third of this reach.

Gravel bars and shoals are common in this reach between banks of intermediate height that act as foregrounds to the high-water embankments. The bars extend out from the banks to cover up to half of the low-water channel. At the observed high water the channel downstream of Monroe was nearly full, due to added local runoff.

Grassy vegetation is well established on many of the bars and helps to make them a permanent (or at least persistent) feature. This helps to maintain the flow stress against the bank opposite the bar and enhances the possibility for scour there. At larger discharges the flow overtops the bars and the vegetation flattens out so that less deflection of flow toward the bank takes place.

Examples of the effects of vegetation can be found near Stations 950+00 and 1025+00. Near Station 950+00 the vegetated point bar at the convex left side of a moderate curve (relative bend curvature of 5 or 6) assists the upstream flow alinement in forcing the low flows strongly against the right bank. That bank has been eroded and is almost vertical in some places; but a compact gravel hardpan protects the toe of the bank so that erosion is very slow. Vines and brush hang down the face

of the bank from the top. A similar situation occurs in a more localized manner near Station 1025+00. The channel here is comparatively straight but the flat alternating bars cause a low-water meander. At one point near the right bank a strong eddy and deep scour hole have formed opposite the widest part of a gravel bar.

At the large observed discharge, brush at the top of the bank face of the intermediate-level foreground causes local flow disturbances and deflects some of the flow toward the high-water embankment. High-water scour was evident on the left bank upstream of Station 1025+00 and downstream from the Alpine Road bridge (Station 1003+00) and was caused by the deflection of flows from the vegetation growing on the bank of the low-flow channel. At Station 1025+00 the channel is sufficiently wide so that brush on the right bank does not deflect the flow against the left bank, unlike the situation described previously for Station 195+00. Over a long distance near Station 179+00, trees and other vegetation overhang the left bank where the channel is a wide slack-water reach. High-water flows there overtop both banks but are not deflected appreciably by this vegetation. The flow adjacent to the opposite bank is not noticeably affected by deflected flows.

At one location not far downstream from Monroe a zone was encountered where both banks are flat and cattle evidently could come to the water's edge. A barbed-wire fence extends across the river at the upstream end of this zone. Bank vegetation here is sparse and the banks are scou[illegible]n many places. The reason for the flatter banks here is not know[illegible]erhaps it reflects a pre-channelization condition or cattle wear-and-tear coupled with erosion.

SUMMARY

Observed field situations revealed that the meandering behavior of the Willamette River and the South Santiam River (one of the principal tributaries) does indeed lead to bank erosion and channel shifting. Relatively permanent stability of the channel position is only found in association with rock outcroppings on the South Santiam. Elsewhere, the rate of erosion and channel change is quite variable. In some places, active shifting is evident; at other locations the channel appears to have been stable for many years or even decades.

Vegetative protection covers most streambanks and contributes importantly to their stability. The immediate upstream flow alinement is also significant with regard to bank stability.

Eroded banks lacking vegetative cover are invariably steep. Erosion of high banks in old, compacted formations has resulted in toe deposits where vegetation has become established and offers some protection from further erosion. Soil types vary along the river and individual streambanks often show layering of the sediment deposits. Often the soil and gravel deposits near the base of a streambank are more resistant to scour than overlying soils and provide a protective toe to resist bank erosion. The Linn Gravels and Diamond Hill clays of the Rowland Formation are of greatest significance in providing this toe protection.

Past dredging and spoil disposal appear to have contributed to channel stability. Sand-and-gravel removal at point bars likewise appears to have had a beneficial effect on some concave banks.

Excessive vegetative growth and debris accumulation were observed to have undesirable effects in some situations. They contribute to bank erosion when they occur on point bars and other channel bars and in narrow reaches where the opposite bank had insufficient protective cover.

Observations along the Long Tom River (another principal tributary), where bank shaping and vegetative plantings had been applied extensively, show general bank stability but many local erosion problems. Grasses, either alone or in combination with revetments, provide much protection. Local bank irregularities and bars cause bank scour and toe erosion at several places.

VI. IDENTIFICATION OF POTENTIALLY APPLICABLE NATURAL STABILIZATION METHODS

IDENTIFICATION OF APPLICABILITY

In this chapter, the available literature on natural means of streambank stabilization (reviewed and summarized in Chapters II and III) is related to the general river features that are pertinent to streambank erosion in the Willamette River and its principal tributaries (reviewed in Chapter IV) and to the more specific river features found at selected field locations (reviewed in Chapter V). The intention of this chapter is to identify those natural methods of streambank stabilization that are potentially applicable in the Willamette River Basin. However, the methods are not developed in detail in this chapter. Further exploration of technical aspects of these methods is made by means of laboratory experimentation and reviewed in Chapter VII. Economic costs are examined in Chapter VIII. Consequently, full development of the methods that appear feasible and effective is deferred until Chapter IX.

The pertinent hydrologic, hydraulic and geomorphic features of the Willamette River and its principal tributaries (Chapters IV and V) establish the conditions under which streambank stabilization measures must serve. These features are not identical with those in other river basins. Therefore, bank stabilization techniques that have been successful elsewhere may not be applicable or may need modification before

application in the Willamette Basin. Applicability can best be determined by comparing the types of river features required for successful application of a given technique with those to be encountered in the Willamette River and its principal tributaries.

APPLICABILITY OF BANK SHAPING

The reviewed literature supports the idea that flattening the slope of a river bank will be beneficial in retarding erosion. Several facets of streambank shaping appear to be applicable to the Willamette River and along principal tributaries. Bank shaping will not offer a complete solution, even if used in conjunction with vegetation and riparian land management, but should help retard the rate of erosion. The major drawback to the successful use of bank shaping is the overpowering ability of the Willamette River to meander. The velocities and forces of the flow are so great that total control of channel position calls for massive and extensive bank stabilization exceeding that attainable by natural means alone.

Discussion of the use of bank shaping in the Willamette Basin is organized here by consideration of three categories of streambanks: those along straight reaches, those that form convex banks, and those that form concave banks.

Banks Along Straight Reaches

Perhaps the principal concern along straight reaches of the river should be the reshaping of false points and other bank irregularities

so that local eddies are not generated which can scour the bank just downstream or deflect the flow against the opposite bank. Reshaping should make the local bank alinement and bank slope compatible with those of adjacent portions of the bank, eliminating all setouts and setbacks. For example, the resistant false point on the right bank of a straight reach of the Willamette River at RM 137.5 could be reshaped to eliminate the large flow deflection and eddy it causes. The soil at the base of this bank irregularity and at the base of the adjacent banks appears to be of similar cohesiveness and resistance to scour, such that removal of the irregularity should not expose a weaker bank material that could erode more easily.

Where one or both banks of a straight reach are being scoured and undercut by a fairly uniformly distributed flow, it may be that the local channel capacity is insufficient. Here, bank shaping can be beneficial both in expanding the channel cross section and in providing a stable slope on which vegetation can become established to offer a protective cover to the reshaped bank. For example, this approach might be effective along the left bank of the Willamette River near RM 141 if erosion and loss of protective vegetation continues and if new vegetation cannot be established on the steeper eroding banks. Such reshaping must provide smooth transitions to merge with existing vegetated banks just upstream and downstream, so as not to aggravate their potential for erosion.

Bank erosion problems along some straight reaches may be readily identifiable as being caused by gravel bars in the channel. If these

bars are part of an alternating bar sequence in the reach, then bank shaping, together with vegetative plantings, may be a viable approach to controlling the problem. However, if the gravel bar causing bank erosion is subject to growth in size due to some upstream influence, then bank shaping might not be very effective because no control is exerted over the cause of the problem. For instance, the gravel bar at the right side of the Willamette River at RM 133.15 is subject to slow growth because of a gradual bend just upstream; bank shaping at the left bank will not be effective if gravel deposition continues at the bar and causes it to further encroach upon the channel capacity. As another example, the bar at RM 89.4 in the Willamette appears to be a transverse bar at a crossing but to have a tendency toward conversion into a central bar. As long as such growth is stunted, bank shaping may be of some help in erosion control. But if the growth of a central bar becomes rapid the flow will be strongly forced against one or both banks and effectiveness of bank shaping will diminish. A mid-channel bar near Station 215+00 in the Long Tom River presently causes no damage to mechanically sloped and vegetated banks, showing that such measures can be effective if bar size is stable.

A somewhat different situation in the nearly straight reach of the Willamette near RM 93 involves the flow division about a large gravel bar (Budd's Island). The straight flow passes on the west side of the bar. Because of the very slight curve of the channel, gravel has been able to deposit across the upper end of the channel that flows on the east side of the bar. Debris has also stranded there. These occurrences

favor a progressively greater proportion of the flow moving through the west channel and the eventual abandonment of the east channel. Bank shaping at the west channel will help improve the channel capacity but may be insufficient compared to the added flow in that channel resulting from the upstream growth of the bar. In such a situation, supplemental measures such as channel bed shaping and debris control would be helpful.

Convex Banks and Adjacent Point Bars

Convex streambanks are situated in protected zones of small velocity and small shear stress. Therefore, any bank or bar shaping undertaken at convex banks would not be intended so much to protect them as to protect the concave banks at the opposite side of the channel. The essential feature of bank shaping in this case is that of removal of point bar material from the concave side of the channel in order to widen the waterway and relieve the shear stresses exerted by the flow against the concave bank.

The shaping of the convex bank and point bar may be subdivided into that which might be done above the summer low-water level and that which might be done below this level. Measures involving shaping above the low-water level to reduce bank erosion might be termed "bar scalping"--reducing the overall level of the top surface of the bar. As a result, flows greater than the low-water discharges have room to expand in a larger channel. Hence, channel velocities and shear stresses during moderate and larger discharges should be less at the concave bank because of the increased channel capacity.

Reshaping below the low-water level to completely remove the point bar involves excavation of the streambed rather than the bank (as does bar scalping). Complete removal includes that part of the bar submerged to shallow depths by low flows as well as the exposed point bar to depths below the low-flow level. Complete bar removal will result in a larger waterway for all flows and will thus relieve the shear stresses being applied to the concave bank.

In reshaping the convex bank by removal of part or all of the contiguous point bar, the reshaped bar is likely to be not only lower but also flatter, approaching a horizontal surface. Hydraulic constraints concerning this reshaping are not as important as fishery constraints, as little particular concern need be given to scour protection at the convex bank but considerable attention must be given to the avoidance of potholes where fish might become trapped during receding streamflows. Fishery constraints also arise with respect to disturbance of the streambed and to turbidity resulting from reshaping of the point bar. Water quality constraints can be met for the reshaping work done above low water but will necessitate special permission for any work done below the low-water level.

Neither of the described forms of bank and bar shaping at the convex bank is long-lasting. These approaches to control of the erosion problem do little to influence the upstream flow alinement at the entrance to the bend. The main flow still tends toward the concave bank, secondary currents still develop, and gravel is still brought toward the inside of the bend, there to deposit and cause regrowth of

the point bar. Hence, periodic reshaping of the point bar will be required, perhaps annually.

The extensive removal of the point bar at RM 93.5 illustrates the beneficial increase of waterway and the reduction of concentrated flow at the concave bank. At higher flows there is no apparent need for reshaping even though a few years have elapsed since bar removal occurred. (The conditions for low flows were not observable to determine the extent of redeposition that may have occurred near the water's edge.)

Concave Banks

Observed concave banks in the Willamette Basin are almost always steep. These are zones where the river is advancing, scouring the toe, undercutting the bank and providing suitable conditions for bank caving to occur due to saturated banks, falling river levels and unstable steep slopes.

Bank shaping along concave streambanks has limited applicability for the Willamette River and large tributaries like the Santiam and McKenzie but greater applicability for moderate sized tributaries such as the Marys River or those with substantial upstream flow regulation (e.g., the Long Tom). The tendency for meandering is so great over much of the length of the Willamette that shaping done only on the concave bank would be ineffectual at the sharper curves or at points of abrupt change of flow alinement if nothing is done to also control flow alinement and curvature.

The critical problem to be dealt with in considering bank shaping at the concave bank is toe scour at the base of the shaped bank. In the

Willamette River, sharp curvature and abrupt alinement changes produce very large velocities and shear stresses against the concave banks and very strong secondary currents that would quickly remove any dislodged bank material. Consequently, even if the concave bank had been greatly flattened to reduce velocities, sufficient shear stress will remain near the base of the slope to scour away the toe, leading to undercutting of the bank. Because velocities and shear stresses are smaller on the smaller principal tributaries (e.g., the Mary's River), better success can be expected there.

Shaping of the base of the concave bank below the water line is possible by means of a drag line. Turbidity of river water will result during such reshaping. This can present a water quality problem that must be dealt with.

Bank shaping must be combined with vegetative protection above the summer water line. But something more substantial and massive would appear to be needed below the summer water line to give toe protection at sharp and abrupt bends of the Willamette River.

When the possibility of shaping the convex bank and its point bar is included, bank shaping at the concave bank has increased applicability in the Willamette and its tributaries. In this case, a significant attempt at temporarily reducing the flow strength at the concave bank may be possible, so that vegetation can become established on a flatter bank there and shear stresses against the toe can be diminished. Unfortunately, this bank shaping combination must be repeated periodically because little or no influence is exerted over upstream flow alinement at the entrance to the bend.

One aspect of shaping a concave bank that appears likely to be successful in the Willamette and its tributaries is the removal of false points and irregularities in the alinement of this bank. Reshaping the irregular bank features so that they blend with the adjacent bank can eliminate the added shear stresses produced by eddies generated at the irregularity. This approach might be used at RM 99 on the Willamette, where dumped rubble creates small irregularities and local eddies. But at RM 102.0 on the Willamette, the local hardpoint helps to deflect the flow into a left hand turn. Therefore, reshaping to remove this bank irregularity would not be beneficial, as a more direct attack on the concave bank a short distance downstream would result.

On a more extensive scale than discussed above, shaping of the concave bank could be applied to a hydraulically desirable future alinement (rather than at the present alinement) for a much more gradual curve with a larger relative bend curvature and with a smooth entry and exit. In effect, the riparian owner would have to accept the inevitable loss of a concave bank, forego the short-term use of the riparian land, and begin shaping a new bank at a location away from the water's edge through fields, pastures or woods with the expectation that this will result in suitable hydraulic conditions and minimal bank erosion once the river has advanced through the intervening berm.

Local Inflows at Banks

Local creeks, culverts and other types of outfalls intersect the river banks at many locations. There is a potential for local erosion

wherever such local inflows to the Willamette River and its principal tributaries occur. This results from scour caused by the entering flow, by deflected river flows, and by eddies generated at these entry points.

The angle of entry and alinement of the incoming flow can be controlled to try to avoid erosion. The bank and outfall structure can be shaped so as to minimize flow disturbance. For example, the culverts entering the Long Tom River in a manner similar to those at Station 188+75 and Station 240+00 could benefit from better control over bank shape (in this case involving stone riprap).

Dredge Spoils

No mention was found in the reviewed literature of the use of dredge spoils to provide bank shaping and erosion control. Yet in many reaches of the Willamette, streambanks have benefited from this activity. This has involved dredging of bars that have caused shallow zones and have hindered navigability.

Removal of part of a bar or shoal results in a disturbance of natural energy dissipation mechanisms and sediment transport constraints. The bars offer hydraulic form resistance that must be overcome by the river, expending some energy that might otherwise be available to cause greater sediment transport. However, the bars also deflect flow toward the banks. Dredging of the mid-river portions of a bar has the effect of reducing hydraulic form resistance, allowing more river energy to be devoted to mid-channel sediment transport, and somewhat relieving the deflection of flows toward the streambanks.

Placement of the dredge spoils against the banks (done by means of a pipeline in the Willamette) provides a protective blanket through which the river must cut before causing additional bank erosion. Consequently, mid-channel dredging coupled with streambank spoil disposal offers an effective temporary control over the bank erosion. The channel capacity is roughly the same as before dredging, as the loss of cross-sectional area near the banks is balanced by the gain of cross-sectional area in the dredged zone. However, the meander mechanisms will cause dredged areas to eventually refill with sediment and the spoil banks to be scoured away in most reaches where bank erosion has been a problem. Therefore, periodic redredging will be necessary to maintain bank protection by this technique.

APPLICABILITY OF VEGETATIVE MANAGEMENT

Vegetative management on river banks has some applicability for the Willamette River and its main tributaries, both in retarding erosion and in providing bank stabilization. In-stream, adjacent-to-the-bank vegetation management appears to have greater applicability, particularly to aid in avoiding or alleviating erosion that might otherwise occur due to snags and other vegetative debris.

Discussion of vegetation management is organized here to first deal with the subject as it is related to the size of vegetation. Then additional remarks are made concerning particular locations where vegetation management is important.

Grasses and Bushes

Short grassy vegetation appears to be most important with respect to providing a root matrix that can hold the soil together. It also serves to provide a flexible layer that helps diminish the shear stress of the flow against the protected soil. To be effective, grasses must form a thick growth. Such situations can be seen along the Long Tom River. At Station 177+25, for example, a concave bank in a fairly sharp curve is effectively protected by only a grass cover.

Vines and other brushy vegetation also appear to be effective in retarding erosion. The thickness of such growth provides a larger buffer zone between the flow and the bank than does grass. This greatly diminishes the shear stress exerted by the flow against the bank. Such vegetation catches small litter to add to its protectiveness. Thorny vines also protect the banks by discouraging access and thus preventing the detrimental effects of trails.

Because bushy vegetation is effective, management is needed to assure that it does not cause problems nearby. The larger that a dense bushy growth becomes, the more effective it is likely to be in protecting the underlying soil. Large growth not only provides a longer distance over which velocities can diminish, reducing the local velocity gradient and shear stress, but also protects the bank by deflecting the flow. The local benefit of deflecting the flow can become an adverse effect elsewhere. Erosion may result just downstream at the same bank due to eddies swirling off of the bushy growth into an exposed area. Flow deflected by heavy brush can also cause damage at the opposite

bank, as noted near Station 195+00 on the Long Tom River. Therefore, growth control (pruning) to regulate brush size and its uniformity is important. Because the desirable size will be limited by channel width, judgment must be used, based upon observation at the site, in pruning bushy vegetation to a length such that eddies and deflections cause no adverse effects.

In spite of the bank protection offered by heavy growths of bushy vegetation, bank failures have been noted. For example, such failure is locally evident near RM 141 on the Willamette River. In this and other cases, it would appear that toe failures rather than vegetation failures were involved.

Revegetation of scoured zones with grasses and bushes is an important aspect of vegetation management applicable to the Willamette River and its tributaries. Particularly where bank erosion has occurred in straight reaches and provided a somewhat wider channel, it may be possible to establish a combination of quick-growing grasses with vines and other brush. The effectiveness of revegetation would be greatly enhanced by first providing some bank shaping to give smoother flow locally. To the extent needed, slope flattening should also be provided to give the vegetation a good foothold.

Numerous kinds of grasses and bushes grow well along the banks of the Willamette and its tributaries. Their ability to grow rapidly and to flourish depends upon the soil characteristics as well as their position with respect to the low- and high-water levels. Some dozen or so varieties of annual grasses and a much larger number of perennial grasses,

forbs, herbs and legumes grow well along streambanks. Among these several were noted in the literature as being suitable: tall and creeping red fescues, rye grass, bromes, vetches, Reed canary grass, birdsfoot trefoil, meadow foxtail and bentgrass. Many low shrubs also flourish along the Willamette Valley streams: blackberry, poison oak, swordfern, bracken fern, snowberry, thimbleberry and several types of roses are common.

Trees

Trees and other large vegetation on the streambank are an important form of vegetative bank protection. The importance of the root system in holding the bank line against large velocities in a straight reach is evidenced near RM 137 to RM 138 of the Willamette River, even though local scour also occurred because of the root systems. The importance of not only roots but also the tree branches in providing a buffer zone against the scouring action of large discharges is evidenced along RM 140 to RM 141 on the Willamette. However, in curved reaches the toe scour at the concave bank can undermine a bank previously protected by trees and cause its erosion. This may be seen at the mouth of Booneville Channel just upstream of the Corvallis Water Treatment Plant (near RM 134.5).

Trees near the top of the bank are also beneficial. Their root systems help to hold the soil together. However, timely removal of tall trees from the brink of an eroding bank appears important to help slow the rate of erosion. If not removed, trees at the edge of the bank may

weaken it. Because of the great tree weight that must be supported, an overload condition and cave-in are likely at saturated riverbanks during the time of a falling river level. Alternatively, soil loosening at the brink of a bank may be caused by a wind storm. In this latter regard, a wide zone of tall vegetation near the bank will provide wind shelter so that windfalls along the bank are less likely.

Several varieties of trees and large shrubs grow well along the banks of the Willamette and its tributaries. Some become established in very moist surroundings and tolerate periodic inundation during winter months. Others do best at the top of the bank where the risk of inundation is low. To establish vegetation as low as possible on the bank, the willow family is probably most suitable. Several of the dozen or more native willow species grow well along the Willamette, both as shrubs and as trees (distinguished in that a tree has one well-defined stem two or more inches in diameter at breast height, has a crown of foliage, and has a height of at least 10 feet). Willows stand water as well as any other tree, grow on poorly drained land, and sprout easily from stumps, branches or roots. They are commonly found on point bars and other bars not subject to severe winter scour and grow almost to the low-water level. Black cottonwoods, the principal species of poplar native to the Willamette Valley and a branch of the willow family, have many of the same attributes as the willows. They are commonly found on the higher portions of bars and on low floodplain terraces. They, too, are fast growing, water loving, and sprout easily from cuttings. Other

trees that grow well along Willamette Valley streams include red alder, Oregon ash, Douglas fir, bigleaf maple, and Oregon white oak. Tall shrubs that grow well along Willamette Valley streams include Cascara buckhorn, black hawthorn, western hazel, and serviceberries.

Debris Management

Removal of individual fallen trees on the river bank or in the river adjacent to the bank provides an effective means of vegetation management. Isolated fallen trees can create eddies that cause the flow to swirl against unprotected nearby banks. Hence, removal of such trees or their placement in a zone with other similar material to form a protective buffer will help to alleviate erosion.

Similarly, debris removal from the channel can eliminate obstacles that may deflect the flow toward the bank. Stranded debris, if not removed, may encourage secondary currents and bar formation in the wake of the debris. This would eventually lead to flow deflections toward the river banks.

Bar Vegetation Control

Vegetative management at point bars in river bends appears likely to be particularly effective in the Willamette and its principal tributaries. Growing vegetation, partly protected by accumulating debris from periodic inundations, provides a large degree of hydraulic resistance. Hence, velocities of inundating flows are often small and much finer-sized sediment can deposit, enhancing the further growth of point bar vegetation. While this may be desirable in order to provide a

permanent point bar that eventually becomes part of the floodplain outside of the active river channel, it greatly encroaches upon the waterway and sustains high velocities near the concave bank. Therefore, clearing of vegetation and debris from point bars will increase the waterway available for large discharges and should thus relieve the velocities and shear stresses exerted at the concave banks.

The concave bank at RM 108 to RM 109 on the Willamette provides an example of new point bar vegetation growth presently that resembles conditions found at RM 140 a few years ago. However, today the point bar vegetation at RM 140 is much larger and extends nearly to the low-water line. Large discharges do not gain much increase of waterway because of the heavy point bar vegetation. As a consequence, erosion is taking place at the opposite bank during high-water periods. Similar problems can be anticipated in the future along RM 108 to RM 109 near the revetment protecting part of the curve. On a smaller scale, involving grasses rather than willows on a point bar, the same type of problem was noted at Station 950+00 on the Long Tom River. Here, vegetative management would also help, but to a lesser degree than would the removal of part of the point bar (both would be temporary solutions to the problem).

Vegetation management on gravel bars in straight reaches can also benefit streambank erosion control. Two examples of where such control would be beneficial are on the Long Tom River at Stations 215+00 and 1025+00. In both cases, only short vegetation is involved. In the first case, the adjacent man-shaped bank slopes and thick brush cover presently

prevent bank erosion. But greater growth of vegetation on this central bar could lead to bank erosion. In the second case, bank erosion has already occurred opposite an alternating bar. The bar is quite wide and this may have aggravated the local erosion.

Toes of Eroded Banks

Vegetative plantings at the toes of recently collapsed steep banks, where the soil has not yet been washed away, could offer some bank protection. This condition was noted in a gradually curved reach of the Willamette River near RM 102 to RM 103. There, natural growth at the toe of a bank some 60 feet high included young trees. A similar situation was found at the base of a high bluff on the South Santiam River at RM 15.8. Low flows impinge on the bank but a wide high-water channel provides flow relief during winter runoff. At lower banks, 10 to 20 feet high, the amount of collapsed soil at the base may limit the effectiveness of toe plantings.

Prompt planting of recently collapsed soils with willow cuttings and quick-growing grasses should have some success along straight reaches or those where channel curvature is gradual. Less likelihood of success can be expected at sharper bends where the flow impinges more on the bank and secondary currents are stronger, giving little chance for the eroded soil to remain in place very long.

Flow Retardation at Eroded and Abandoned Waterways

Vegetative plantings can be quite beneficial in retarding flow through sloughs, cutoffs and other channelized zones where much flowing

water would be detrimental to bank stability. The intention would be to provide a rapid growth of dense vegetation, including tree cuttings and debris, so that the hydraulic resistance is greatly increased, the local waterway is choked, discharge is reduced, velocities are low, and transported sediment can deposit to progressively fill in the waterway. This should be done only where the waterways do not give needed relief for flood flows in the river (thus giving relief to stresses at banks) but should not be done across beneficial high-water channels.

Some locations where this type of vegetative management would be most effective are at the inner sides of horseshoe curves, at the bases of some large point bars, and where the channel has shifted about, leaving abandoned channels with poor alinements to existing banks. In a different situation, at RM 99 on the Willamette River, a riparian landowner has successfully used tree trunks at a low, slightly concave bank to reduce runoff velocities from agricultural lands and to partially block flood flows that overtop the bank there. Vines and other bushy vegetation are growing there to add to the flow deterrent effect of the tree trunks.

Vegetative Structures

Vegetative structures in the form of fences can have an important use on the Willamette River and its principal tributaries. Fences consisting of a mesh of dead limbs and living cuttings or plantings can be effective as natural debris barriers to retard overbank flow at low ground in bends and elsewhere, including high-water chutes and potential

cutoff channels. Dumped debris can be incorporated into such vegetative structures. With a few years of growth to become strongly established, this type of vegetative protection should serve almost as well as the timber debris barriers that have been constructed at many locations to accomplish the same purpose. Such structures are needed for the less-frequent flood discharges and are likely to be in "active" service only a few days per year.

The use of flat brush mats, made of many small branches, can help vegetation become established on eroded banks between flood seasons. The abundance of willows on point bars provides a source of cuttings that could be assembled into loose protective mats. These could be anchored with string or wire to control scouring velocities from fluctuating summer streamflows until young plants grow and develop strong root systems. As the brush mats deteriorate with age, they will become buried and held in the new vegetation. These will find best applicability at eroded banks of gradual curves and straight reaches, where near-bank velocities are not very large (i.e., less than about 5 feet per second). If washed away, the small size of the branches (3 or 4 feet long) will allow them to readily become stranded at other downstream banks where they will do little to aggravate erosion but instead might offer some protection if accumulated with other small debris. The only problem that might be anticipated is their catching on in-stream snags and increasing local hazards there.

The more elaborate vegetative structures that have been used in rivers adjacent to streambanks might have limited application in certain

locations in the Willamette Basin. For example, use of cabled trees along the bank or of whole-tree deflectors extending from the bank might be appropriate in a straight channel if it is locally wider than its typical width in that part of the river, in a straight or curved channel where the velocities do not become too large (e.g., they remain less than about 10 feet per second) and for gradual bends with relative bend curvatures greater than perhaps 6 (preferably with a low point bar opposite the protected bank). Then anchored trees backfilled with brush may be able to withstand the onslaught of high waters without breaking loose. The smaller the river, the more likely is the method to be successful. The width constraint mentioned above is suggested so that local flow constrictions do not occur which would result in locally larger velocities and increased scour potential.

Vegetation Combined with Mechanical Methods

Vegetation used in combination with mechanical methods appears to have general application. This approach does involve use of massive structural techniques; therefore, only brief mention of applications is made here.

The key problem in arresting bank erosion in the Willamette Basin is that of protecting the toe of a concave streambank. It is at the toe that vegetation used alone is inadequate to offer protection in most typical situations, due to the inability to establish growth in the zone of continuous inundation. When soil properties offer a favorable toe to resist erosion, then vegetation above the water can add greatly to bank

stability by protecting overlying layers of soil that may be less resistant to erosion. But where the soil at the base of the bank is not able to resist the scouring action of the river, only a massive technique is likely to offer the needed protection.

Possible applications include use of a continuous stone revetment to protect the toe of the concave bank with grassy and bushy vegetation above the toe to the top of the bank and beyond. Also, a line of timber piles out from the bank can be established and backfilled with brush, branches and debris to form a permeable barrier and thereby induce sediment deposition in zones of low velocity within the brush. Then, planted bank vegetation can be used to add further protection and bank stabilization. Steel jacks, wired together, can be used in the same manner with living and dead vegetation.

The continuous stone revetment discussed above might be used in many locations in the basin. The piling and jack techniques would be most effective if velocities remained below about 10 feet per second at all times. The latter techniques would also be effective for blocking abandoned channels and sloughs or for controlling overland flow.

APPLICABILITY OF RIPARIAN LAND MANAGEMENT

Several aspects of riparian land management appear to be important for overall reduction of streambank erosion and enhancement of bank stability.

Top-of-Bank Management

Land use near the top of the bank can be managed to provide a continuous zone of vegetation for some distance back from the top of the bank. An arbitrary width might be established based upon an estimated growing time of perhaps three years for establishment of a thick root zone on newly planted soil. Hence, the width of the vegetation zone might be set at about three times the likely annual rate of bank erosion. This width would be meaningful where top-of-bank scour is a problem. It would be less meaningful where toe failures are the principal cause of bank erosion, rather than top-of-bank erosion and gullying. The goal of the vegetation zone would be to provide a root matrix and surface soil protection against overland erosion and against gullying from concentrated surface runoff by retarding such flow and encouraging infiltration.

Irrigation practices near the streambank can be such that protective vegetation and cultivated plants receive the needed amount of water but that excessive quantities of water are avoided. When the field capacity of the soil is exceeded, excess water will mainly serve to build up the water table of the soil and the level of streambank saturation. Because irrigation water is applied in the summer when river levels are low, a buildup of the bank saturation level would lead to greater seepage forces and a greater potential for resulting bank caving. Because sprinkler irrigation is more common than ditch irrigation in the Willamette Basin, careful control over near-bank water table levels is achievable. Non-cohesive banks should not be allowed to become too dry, as crumbling of some soils may then occur.

Related to the two preceeding aspects of riparian land management is the provision of an efficient drainage system near the bank that not only reduces the adverse runoff effects but also provides control over the nearbank water table level. The reviewed literature mentioned use of parallel drain tiles but no seepage pipe drainage similar to that used at highway road cuts. Experimentation might be valuable in showing whether the technique could be applied to river banks so that the local water table might be drawn down rapidly without large seepage forces whenever the river level recedes as storm runoff diminishes.

Control Over Bank Access and Traffic

The avoidance of trails and paths at the concave banks of rivers is another critical aspect of riparian land management. These not only leave damaged vegetation and bare soil but also cause soil to be dislodged. They also allow concentration of surface runoff and seepage. All of these lead to greater likelihood of erosion at the most critical place for river erosion to take place -- the concave bank. At convex or straight banks little bank erosion was observed on the Willamette or Long Tom Rivers due to trails and paths.

Grazing animals should be kept back from the tops of steep river banks so that they don't strip and trample needed vegetal protection or make paths at undesired locations. At convex bends and on flatter slopes of straight reaches, grazing animals are not likely to cause irreparable damage. Vegetative zones and selective fencing can be used to keep animals away from banks that are the most susceptible to erosion.

Upland Practices

Good soil conservation practices on upland areas are of general importance. With regard to streambank erosion, such practices reduce local surface runoff and prevent the formation of gullies that can intersect and disrupt the stability of a river bank. When such conservation practices are widely and intensively practiced, they can sufficiently alter hydrologic conditions so that more of the precipitation is held on the basin and less enters the streams. This can reduce flood peaks and volumes of runoff, benefiting streambanks as well as providing greater water supplies for basin uses.

River-Related Structures

Care in the design and construction of river-related structures is also important in maintaining or enhancing streambank stability. The most common of such structures are bridges, water intakes and wastewater outfalls. Abutments, piers, intake towers, and pipelines can be designed with due consideration for their effects on the river. Hence, this should be an important aspect of design so that channel stability is maintained or improved. Likewise, the construction of such facilities should be carried out in such a manner as to minimize streambank damage and channel disturbance.

VII. LABORATORY EXPERIMENTATION WITH SIMULATED NATURAL MEANS OF STREAMBANK PROTECTION

LABORATORY FACILITIES

General Features

The laboratory experimentation facilities involve a fixed-bed model and its appurtenant operating and measurement equipment. The model represents a portion of a meandering alluvial river. A schematic diagram is shown in Figure 9.

This model permits study of several channel parameters, each of which can be varied in the model. These parameters include channel configuration (as seen in plan form), channel width (either at the bed or water surface), radius of bend curvature, bank slope, bed slope, bank vegetation, and water discharge. The various possible channel configurations that may be modeled include straight reaches, single bends between straight reaches, and two or more bends in succession. By selection of different combinations of bend radius and channel width, various relative degrees of curvature may be studied. Bank vegetation can be simulated with respect to length, brushiness and distribution pattern along the bank.

The appurtenant features include a water circulation system, a location measurement system, and a flow velocity measurement system.

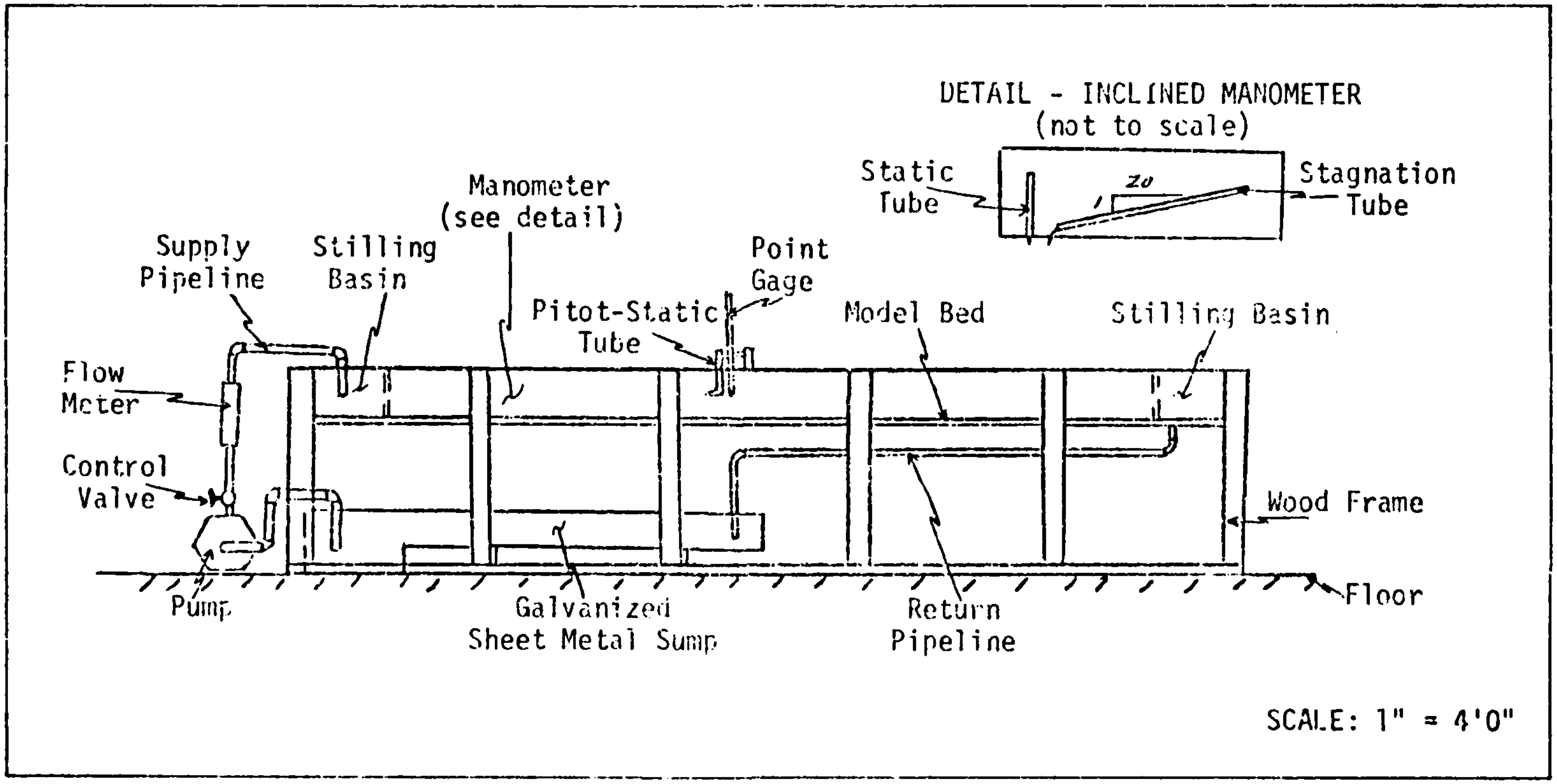


Figure 9. Schematic Diagram of Experimentation Facilities

The water circulation system includes a pump and supply line, a distribution chamber upstream of the model box, a collection chamber downstream of the model box, a return line, and a water storage sump tank from which the pump withdraws and recirculates water.

The location measurement system permits the three-dimensional coordinates of each velocity measurement to be known. The longitudinal stationing is determined from two scales along the sidewalls of the model box. The lateral stationing is determined from a scale fixed to an instrument bridge spanning the model box and supported at the sidewalls. The vertical stationing is determined by means of a point gage attached to a scale supported by the instrument bridge.

The flow velocity measurement system consists of a pitot-static tube connected to an inclined manometer. The pitot-static tube is supported from the instrument bridge and can be positioned to allow measurement at any point in the flow to within 3 millimeters of the flow boundaries. The inclined manometer is mounted on the outside wall of the model tank at the same level as the stream.

The flow velocity measurement and the location measurement systems permit local velocities to be measured, velocity profiles and velocity contours to be developed at chosen cross sections, and boundary shear stresses to be calculated at those cross sections.

Detailed Features

The model was constructed in late 1975 specifically for use in the study reported here. Some details regarding construction and descriptions of the appurtenant equipment are given here.

The rectangular experimentation box is 20 feet long by 8 feet wide by 1 foot deep. It is constructed of exterior plywood and is sealed with several coats of fiberglass resin paint. Two plywood partition walls located 2 feet from either end subdivide the experimentation box by creating chambers at each end measuring 2 feet by 8 feet by 1 foot, one serving as the upstream stilling basin and distribution chamber and the other serving as the downstream collection chamber. Between them is the 16 foot by 8 foot by 1 foot model box. The meandering alluvial channel is modeled within this inner box. The rectangular experimentation box is supported 4 feet above the floor by means of a rigid wood framework. Figures 10 and 11 show many of these features.

The water storage sump tank is supported by the floor and bracing lumber directly beneath the experimentation box. It is constructed of galvanized sheet metal and is 10 feet long by 4 feet wide. It has a shallow end, 1 foot deep, near the return line and a deeper end, 1 1/2 feet deep, near the pump suction line.

A 3-horsepower single-stage centrifugal pump is used to provide flow circulation for the experimentation system. It has a 3-inch suction line and a 2-inch discharge line connection. The pump is mounted on the floor just outside of the sump tank and the outside wall of the experimentation tank.

Piping connected to the pump includes the 3-inch diameter suction line, a short 2-inch diameter discharge line, and an expansion to a longer 3-inch diameter discharge line. The discharge line rises above the outside wall of the experimentation box and drops down into the

Figure 10. Experimentation Box and Velocity Measurement System

Figure 11. Positioning the Pitot-Static Tube (Test 12)

upstream water distribution chamber. There it ends with a tee fitting and perforated pipes to deliver water along the width of the chamber.

A 2-inch globe valve in the discharge line is used to regulate the flow rate to the model. The flow rate is measured with an impact rotometer placed in the 3-inch riser on the discharge line. Maximum capacity of the meter is 300 gallons per minute. Somewhat larger flows can be produced by the pump but will exceed channel capacity for most models tested.

A return line from the downstream water collection chamber to the sump tank completes the piping system. Fourteen feet of 3-inch PVC pipe with two 90-degree bends are used.

The channel model is formed between two sand berms. These are first shaped with a template to oversized dimensions. They are then overlain by roofing paper. The channel lining is then constructed directly on the roofing paper as a thin concrete mortar layer, approximately 1/2 inch in thickness. Vegetative patterns can be placed in the channel by means of adhesives. The material used to simulate vegetation includes burlap cloth and mesh padding of the type commonly used as cushioning in shipping cartons. This type of channel model allows a great deal of flexibility in experimentation.

EXPERIMENTAL METHODS

Measurements Made

Velocity measurements made at several points in the channel cross section constitute the majority of test data. Velocity readings were

obtained using a pitot-static tube and an air-water manometer (see Figures 10 and 11). The pitot-static tube was mounted with a point gage on an instrument bridge. The point gage was attached to a scale so that the vertical position of the water surface and of each velocity measurement could be found. Lateral and longitudinal positions were determined as described earlier. A pitot-static tube with an outside diameter of 0.25-inch was used. Pressure lines of tygon tubing extended from both the pitot tube and the static tube along the instrument bridge and over the outside sidewall of the model box. There, the lines were attached to an inclined manometer, which was fixed on the side of the model. The manometer was composed of two lengths of plexiglass tubing having an outside diameter of 1/2 inch. The pressure lines were attached to the lower ends of the tubes and the opposite ends of the tubes were open to the atmosphere. The static tube was vertical and the total head tube was inclined at a slope of 20 horizontal to 1 vertical (20H:1V). The tubes were mounted against a graphical coordinate system to allow determination of the stagnation and static pressure heads, which subsequently could be converted to flow velocity.

A typical experimental determination of point velocity was made using the following procedure:

(1) The pitot tube was immersed in the flow;

(2) Suction was applied to the tygon tubing to initiate the rise of water in both manometer tubes;

(3) A graphical coordinate grid behind the tube was used to determine the static tube level;

(4) A "zero" reference point was established for the inclined tube by translating the static tube level horizontally to the grid behind the inclined tube and noting its position there on the horizontal scale;

(5) Reading the stagnation tube water level on the grid behind the inclined tube, the horizontal displacement due to the rise of water caused by the velocity's dynamic head could be determined;

(6) This horizontal reading was converted to a vertical rise of water based on the manometer slope;

(7) The point velocity was calculated: $V = \sqrt{(\Delta h_{vert.})(2g)}$.

This system of data collection was used after several other possible methods were considered and experimented with. Though not a rapid procedure, it proved to give satisfactory results.

Each of the 28 tests conducted consisted of the determination of 20 to 30 point velocities in a channel cross section. The readings were taken at different verticals in the cross section. In this way, several channel velocity profiles were obtained.

Velocity contour lines were drawn for the cross sections from each of the 28 different tests. First, however, the point velocity data were normalized by converting them to ratios with the mean channel velocity for each test. This was done to allow the plotting and comparison of several velocity contours for each test. Boundary shear stresses could be calculated for the bed and side slopes using the logarithmic velocity equation. However, due to the qualitative nature of this model study, the point velocities and velocity countours were themselves sufficient to permit the drawing of conclusions from the tests.

Tracing of Surface and Bottom Currents

Surface and bottom flow patterns were evaluated as a supplement to the velocity measurements. This was done for several, but not all, of the different channel configurations involving a curved channel. These proved to be quite helpful in confirming actual velocity readings and general flow characteristics for the different channel geometries.

Surface flows were determined using small circular pieces of paper from computer tape punches. These pieces were released upstream of the meander bend and observed as they progressed around the curve. Velocity patterns and relative magnitudes could be arrived at qualitatively in this manner. Longitudinal and lateral flow components were then sketched on plan views of the different stream channels to provide supplemental information for data interpretation.

Velocity patterns and the effects of shear stresses on the channel bottom were also observed. Sand was distributed in a thin layer along the channel. The model was run for a period of time sufficient to establish a steady-state flow condition. Areas of sand scour and deposition were observed and recorded on a sketch. This allowed a qualitative comparison of surface and bottom velocities for the different channel geometries.

Figure 12 illustrates the tracing of surface and bottom currents.

GENERAL DESCRIPTION OF TESTS

Kinds of Tests

Experimentation dealt with two basic channel geometries. Initially, testing was conducted in a straight channel of symmetrical trapezoidal

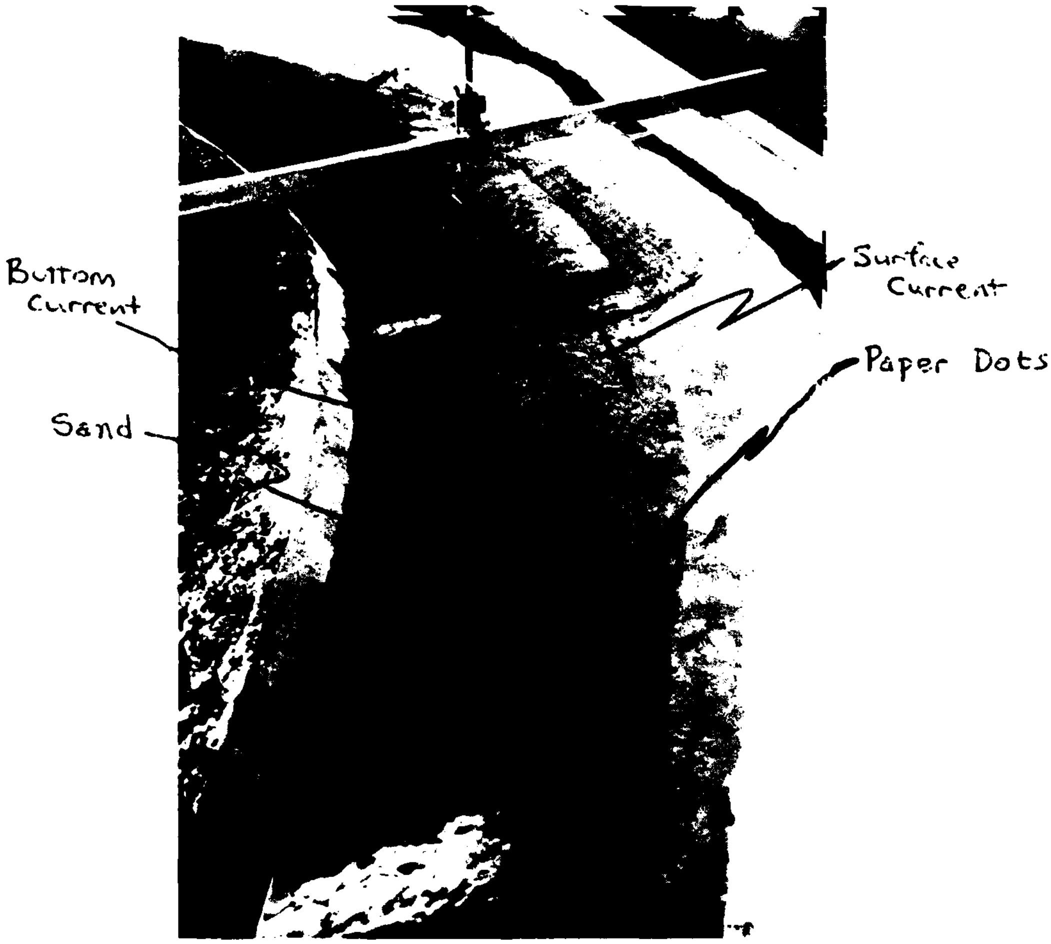


Figure 12. Surface Currents Traced with Paper Dots and Bottom Currents Traced with Sand (View Looking Upstream During Test 13).

cross section. The other basic channel geometry was a curved channel with various trapezoidal cross sections, most being non-symmetrical. A total of 28 test runs were made during the experimental program. Point velocities and their corresponding locations were measured in every run. Surface and bottom currents were observed only in specially selected cases.

The range of hydraulic and geometric parameters covered in testing is summarized in Table 1 and in the next sub-section of this chapter. Parameters that were varied in the testing program included water discharge, channel alinement, geometry of the convex bank, slope of the concave bank and vegetative cover. Vegetation was simulated using burlap cloth and mesh padding in various combinations. The burlap simulated uniform grassy vegetation and the thicker mesh material simulated continuous very thick brush. These materials were used in various combinations.

Parameter variations studied in the straight channel dealt mostly with vegetal cover and longitudinal location of velocity measurement in the channel. The bank side slope was a constant value of 2H:1V for both banks. Both types of vegetation (grass and bushes) were modeled on each bank separately or both banks concurrently. Velocity data were taken at several cross sections along the longitudinal channel axis to determine the effects of several different vegetal configurations upon flow patterns. Flow rates were approximately the same, but not identical, in each test. The flow and stage varied due to the altered boundary roughness and to the encroachment of vegetation, the point bar and the concave bank upon the waterway.

TABLE 1. SUMMARY OF LABORATORY TESTS

Test No.	Channel Geometry[a]	Side Slope H:V	Side Slope Bank	Vegetation Present	Further Description of Channel and Cross Section
Preliminary Tests					
1a	straight	2:1	both	none	1/3 of channel length downstream of entrance (cross section = 9.00')
1b	straight	2:1	both	none	same as 1a but 4 ft. further downstream (cross section = 5.00')
2	straight	2:1	both	bushy - both banks	(cross section = 5.00')
2a	straight	2:1	both	bushy - both banks	(cross section = 9.00')
3	straight	2:1	both	bushy - right bank	(cross section = 5.00')
3a	straight	2:1	both	bushy - right bank	(cross section = 9.00')
4	straight	2:1	both	short - right bank	(cross section = 7.00')
5	straight	2:1	both	none	(cross section = 7.00')
6	straight	2:1	both	short - both banks	(cross section = 7.00')
7	straight	2:1	both	bushy - right bank	data taken downstream of vegetation to study eddy effect (cross section = 7.00')
8	curved R/b = 2.7	1/2:1 3:1	convex concave	none	(cross section = 8.00' for all curved channel tests)
9	curved R/b = 2.7	1/2:1 3:1	convex concave	none	point bar present
10	curved R/b = 2.7	1/2:1 3:1	convex concave	short - concave bank	point bar present
11	curved R/b = 2.7	1/2:1 3:1	convex concave	short, bushy - concave bank	point bar present
12	curved R/b = 2.7	1/2:1 3:1	convex concave	short - concave bank	upstream gravel extension of point bar

TABLE 1, Continued

Test No.	Channel Geometry[a]	Side Slope H:V	Side Slope Bank	Vegetation Present	Further Description of Channel and Cross Section
13	curved R/b = 2.7	1/2:1 3:1	convex concave	short - concave bank bushy - point bar	point bar extended further upstream
14	curved R/b = 2.7	1/2:1 3:1	convex concave	short - concave bank bushy - point bar	channel entrance revision - effective for all subsequent tests
15	curved R/b = 3.1	1/2:1 2:1	convex concave	none	point bar present
16	curved R/b = 3.1	1/2:1 2:1	convex concave	short - concave bank	point bar present
17	curved R/b = 3.1	1/2:1 2:1	convex concave	short - concave bank bushy - point bar	point bar present
18	curved R/b = 3.1	1/2:1 2:1	convex concave	bushy - point bar	point bar present
19	curved R/b = 3.1	1/2:1 2:1	convex concave	short, bushy - concave bank	point bar present
20	curved R/b = 3.1	1/2:1 2:1	convex concave	short - concave bank	no point bar
21	curved R/b = 3.1	1/2:1 2:1	convex concave	short, bushy - concave bank	no point bar
22	curved R/b = 3.1	1/2:1 2:1	convex concave	none	no point bar
23	curved R/b = 4.2	1/2:1	both	none	no point bar
24	curved R/b = 4.2	1/2:1	both	none	point bar present
25	curved R/b = 4.2	1/2:1	both	bushy - point bar	point bar present

[a] Where R = radius of curvature of bend, b = width of waterway, R/b = relative bend curvature (Fig 8)

Tests were conducted in the curved channel for different vegetal configurations, bank side slopes, cross-sectional point bar features, and upstream flow alinement. Short and bushy vegetation patterns were modeled on the concave bank. Bushy vegetation was also located on the point bar for several tests. Side slopes of 3H:1V, 2H:1V, and 1/2H:1V were modeled. A point bar was in place for approximately half of the test runs. The upstream flow alinement approaching the test bend simulated both a sharp turn and a more gradual turn. Flow rates were held constant for tests made with the curved channel.

Grouping of Tests

Tests 1 through 7 dealt with the straight channel having 2H:1V side slopes. Among these, Tests 4 through 7 involved velocity measurements at a cross section midway along the channel, whereas in previous tests these measurements were made at a section either upstream or downstream.

The remaining tests involved the curved channel. In Tests 8 through 11 a sharp upstream bend alined the flow toward the inside of the test bend. In Tests 14 through 25 a gradual upstream bend alined the flow toward the outside of the test bend. Tests 12 and 13 provided intermediate alinements. All velocity measurements were made at a cross section at the center of the bend. Tests 8 through 14 involved a 3H:1V concave side slope; Tests 15 through 22 a 2H:1V concave side slope; and Tests 23 through 25 a 1/2H:1V concave side slope.

For the tests in the curved channel, it was not possible to maintain a constant relative curvature of the bend. However, the situation was

analogous to what might happen with bank shaping. A basic curve was laid out in the model. Discharge was nearly constant; widening the concave bank resulted in a lower average velocity in a larger cross section with a similar flow depth. Thus, the channel width at the water surface increased substantially while the bend curvature radius increased only slightly, causing the relative curvature of the bend to decrease. This ratio varied from 4.2 with a 1/2H:1V concave bank slope to 2.7 with a 3H:1V concave bank slope.

Surface and bottom currents were studied in Tests 10, 11, 14, 16, 17, 19, 20, and 21. For Tests 10, 11 and 14, both low flow and high flow conditions were studied.

EXPERIMENTAL RESULTS

A general discussion of the individual tests and the actual and projected flow patterns follows. Test results consist of data describing point velocities, velocity distributions, surface currents, and bottom currents. Reference can be made to Table 1 for individual channel configurations.

Straight Channel with 2H:1V Side Slopes

Tests 1 through 3a were trial tests to develop measurement techniques. As such, the experimental results are not very reliable or suitable for comparative purposes. Therefore, only verbal descriptions of those results are presented. Figure 13 gives a plan view of the vegetal arrangements used. Tests 4 through 7 provided reliable information and the results obtained are described both verbally and

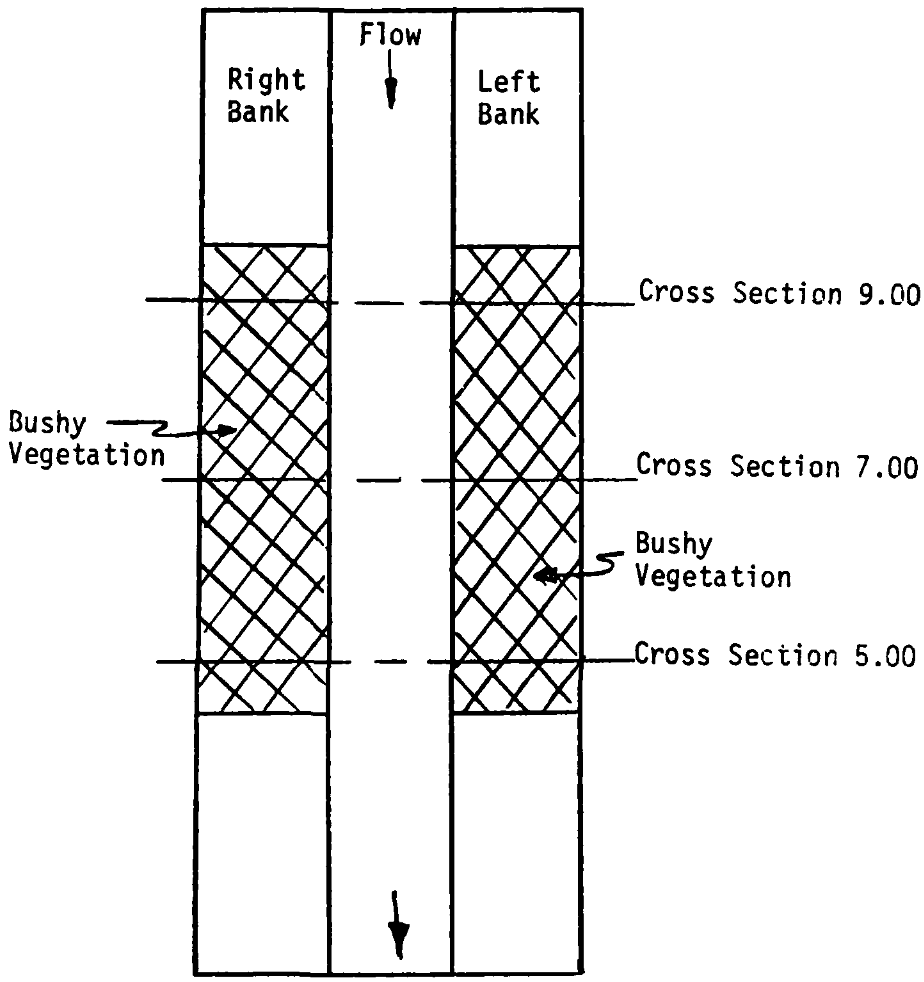


Figure 13. Plan View of Straight Channel with Bushy Vegetation (as used in Different Arrangements for Tests 2, 2a, 3, 3a)

graphically. Figure 14 gives a plan view of the vegetal arrangements used during these tests.

Test 1a: This was the case of bare banks for the straight channel. Data were taken approximately one third of the channel length downstream of the entrance. The velocity distribution was found to be relatively symmetrical about the centerline of the channel. This was as expected for this channel configuration.

Test 1b: This test was similar to the preceding test except that data were taken nearer the downstream channel exit. A higher average velocity and a lower stage were evident due to the hydraulic gradient in the channel and to some exit effects.

Test 2: Bushy vegetation was simulated on both banks (see Figure 13). Velocities were obtained near the downstream end of the vegetal zone. Flows were greatly influenced by this rough cover and the corresponding channel constriction. Velocities in general were quite high and somewhat non-symmetrical, being higher near the right bank. This was probably due to non-symmetrical convergence of the flow along the zone of bushy vegetation.

Test 2a: The same as Test 2 except that data were taken 4 feet upstream. This was near the upstream end of the vegetal zone (Figure 13). Higher velocities were evident in the vegetal zone than upstream. This close to the upstream end of the brushy vegetation there was no evidence of the non-symmetrical flow found in Test 2. Instead, the velocity distribution was quite uniform with seemingly little effect due to increased channel roughness.

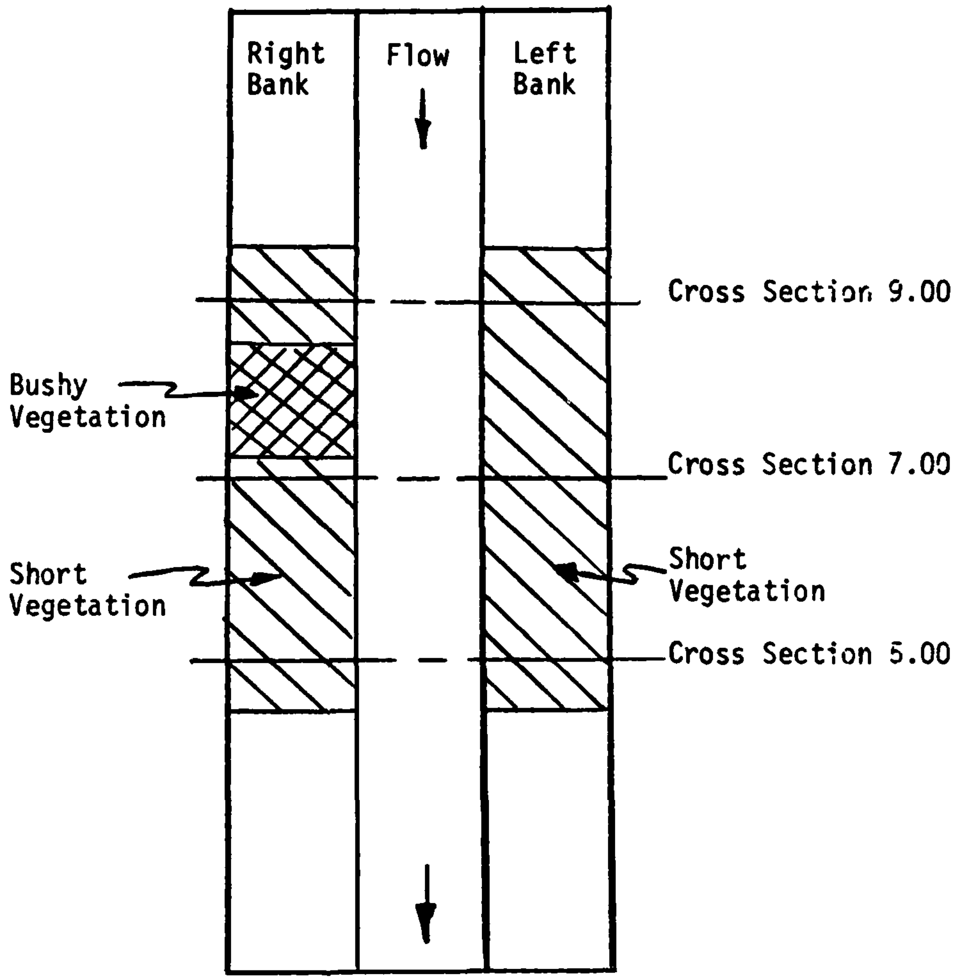


Figure 14. Plan View of Straight Channel with Variable Forms of Vegetation (as Used in Different Arrangements for Tests 4, 6, 7)

Test 3: Bushy green vegetation was simulated only on the right bank. Data were gathered at the downstream end of the vegetation (Figure 13). The increased channel roughness on the right bank, caused by the thick cover there, deflected flows somewhat toward the left side of the channel. Velocities near the coarse vegetation were reduced while velocities were increased near the opposite bank. As this cross section was close to the downstream end of the simulated vegetation, the full effect of the extensive upstream vegetation was experienced.

Test 3a: This was similar to Test 3 except that the cross section analyzed was 4 feet upstream, near the beginning of the vegetal zone (Figure 13). Velocities in this section were more uniformly distributed than those in Test 3. Less effect due to the vegetal cover was noted. This was attributed to the shorter vegetal zone upstream of the cross section. Velocities near the right bank were not lowered as much by the increased channel roughness as at the downstream cross section used for measurement in Test 3.

Test 4: Short grassy vegetation was modeled on the right bank (Figure 14). There was a larger velocity reduction near the banks in this case than that noted in Tests 3 and 3a for bushy vegetation. Higher bank velocities in those tests may have been caused by displaced flow due to extension of the long bushy cover into the central channel near the bed, in contrast to the low profile presented by the burlap material. The normalized velocities and velocity contours are presented in Figure 15.

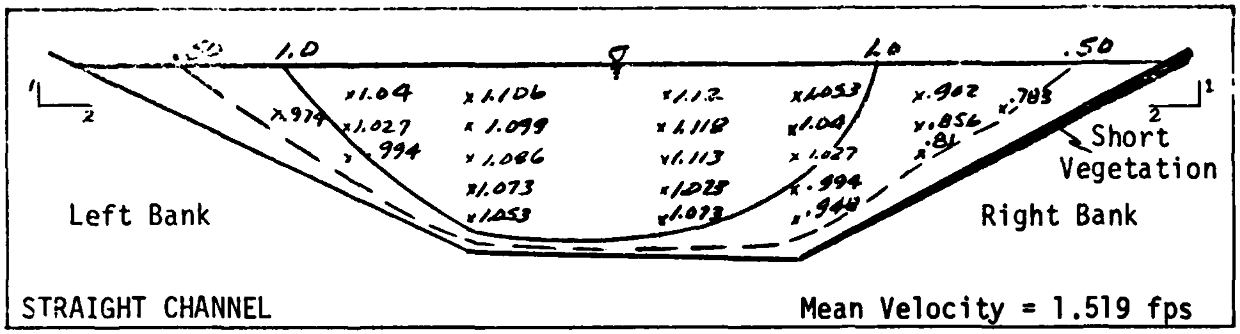


Figure 15. Normalized Velocity Distribution For Test 4.

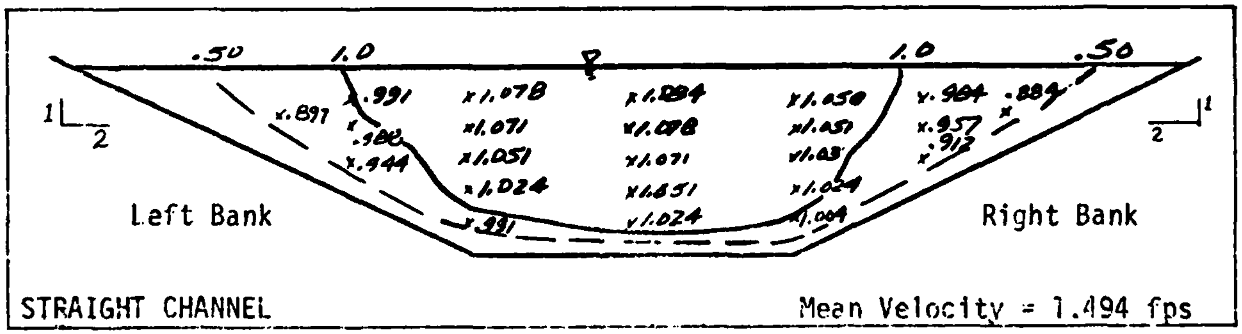


Figure 16. Normalized Velocity Distribution For Test 5.

Test 5: The test conditions were the same as for Tests 1a and 1b except that a section intermediate between those of the previous tests was used. Similar symmetric results were noted. The normalized velocities and velocity contours are shown in Figure 16.

Test 6: Results similar to those found in Test 4 were noted for this channel condition. Short vegetation was modeled on both side slopes, as shown in Figure 17 and by reference to Figure 14. Local velocities were lower near the banks due to the shorter cover compared to data obtained for thicker vegetal material (Tests 2 and 2a). The velocity distribution was fairly symmetrical, as was expected. Figure 18 presents the normalized velocities and velocity contours.

Test 7: Thick brush was modeled locally on the right bank (Figure 14). Velocities were measured at a cross section immediately downstream of this vegetation. Non-symmetrical flow occurred with higher velocities on the left side of the channel. An eddy was noted at the right bank downstream of the isolated heavy vegetation. Resulting normalized velocities and velocity contours are shown in Figure 19.

Curved Channel With 3H:1V Side Slope at Concave Bank

Tests 8 through 11 were conducted with a short point bar. In each of Tests 12 and 13 the point bar was extended somewhat farther upstream. Flow conditions approaching the bend simulated those for an abrupt change of alinement and reversal of channel curvature (from abrupt left-hand turn to gradual right-hand test bend). For Test 14 the upstream approach conditions were altered to simulate a more gradual left-hand

Figure 17. Straight Channel Setup for Test 6 (View Looking Downstream).

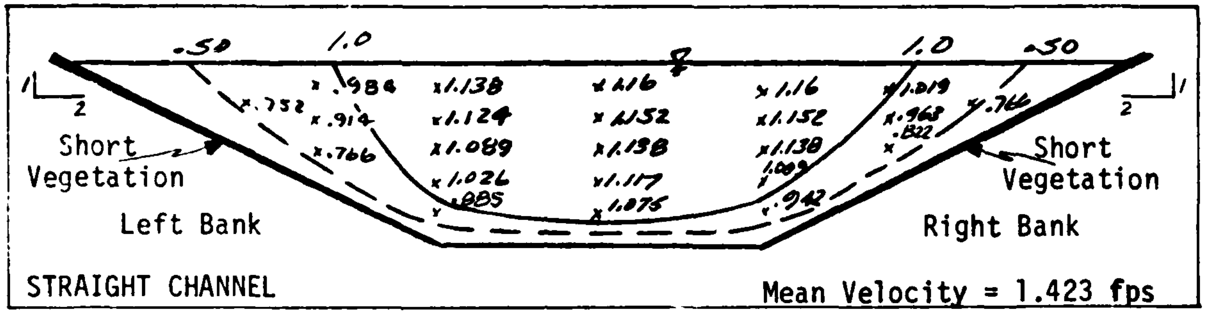


Figure 18. Normalized Velocity Distribution For Test 6.

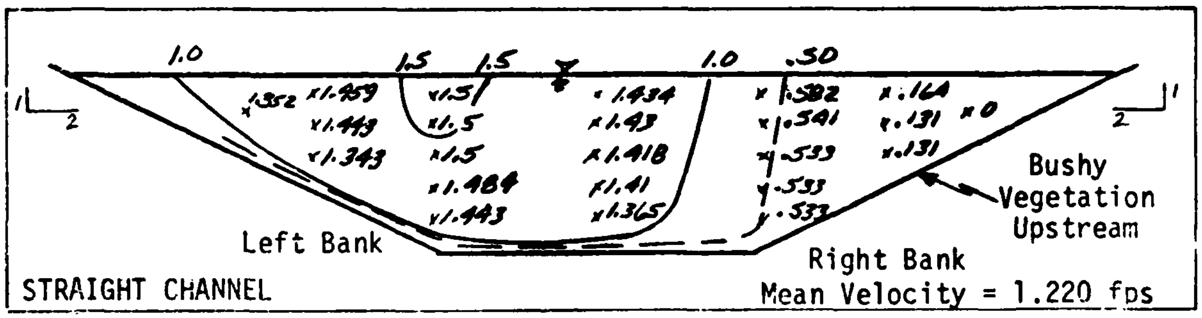


Figure 19. Normalized Velocity Distribution For Test 7.

turn leading to the test bend. Figure 20 gives a plan view of all of the features used in Tests 8 through 14. Figure 21 shows specific conditions for one of these tests.

Test 8: This channel configuration has no point bar and no vegetation. Very high velocities were experienced near the convex bank due to the upstream flow alinement and lack of a point bar. A large eddy formed on the concave bank due to the relatively flat side slope. This effect extended as far into the channel as the bank toe or beyond. Figure 22 presents the normalized velocities and velocity contours.

Test 9: A point bar was built for this and subsequent tests. The bar was inundated during high-stage flows in the model. Very large velocities occurred over the bar due to the upstream flow alinement. Intermediate velocities were prevalent along the deeper part of the channel. The eddy was still in evidence along the upper portion of the concave bank. The normalized velocities and velocity contours are shown in Figure 23.

Test 10: This curve has short vegetation on the concave bank. The point bar is present. Mid-channel velocities were comparatively uniform and slightly larger values were found over the bar, again due to the upstream flow alinement. The short vegetation on the concave bank was probably not too influential upon channel velocity distributions. Small velocities were measured on the concave side slope but they were probably due to the channel entrance conditions and the flat side slope. Bottom and surface currents were also studied. They indicated weak flows at the concave bank and a potential for erosion of only the toe of the

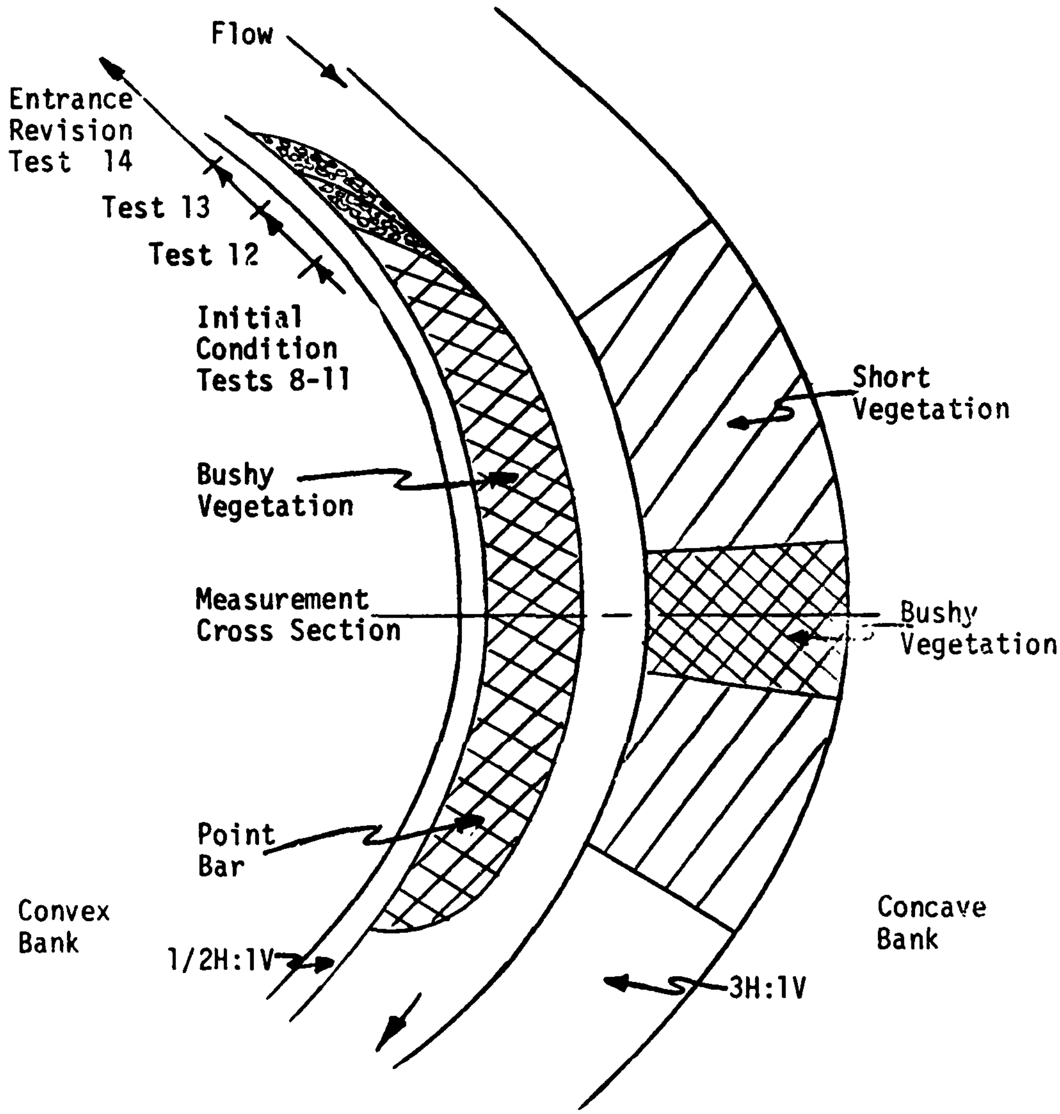
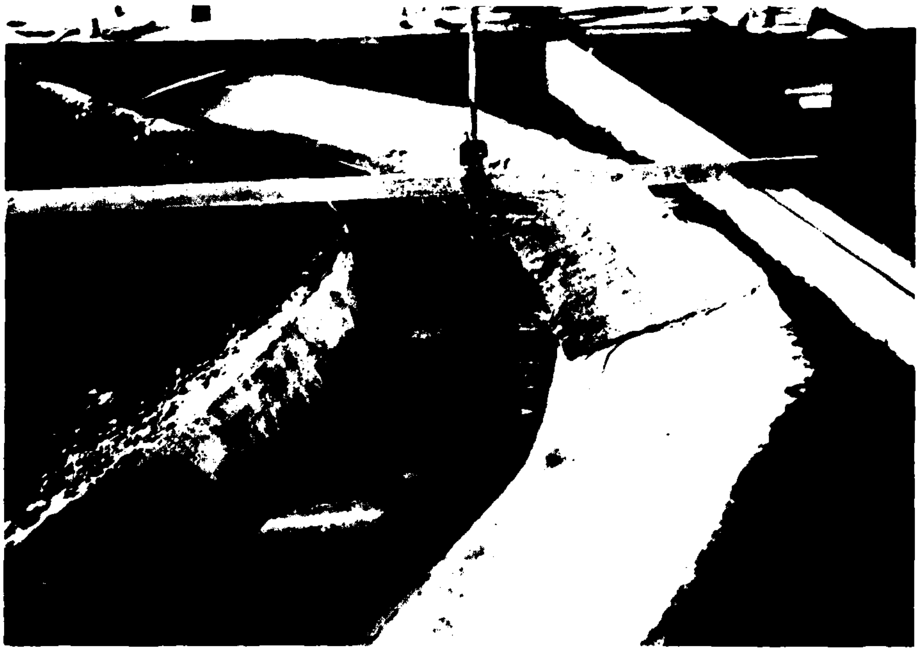
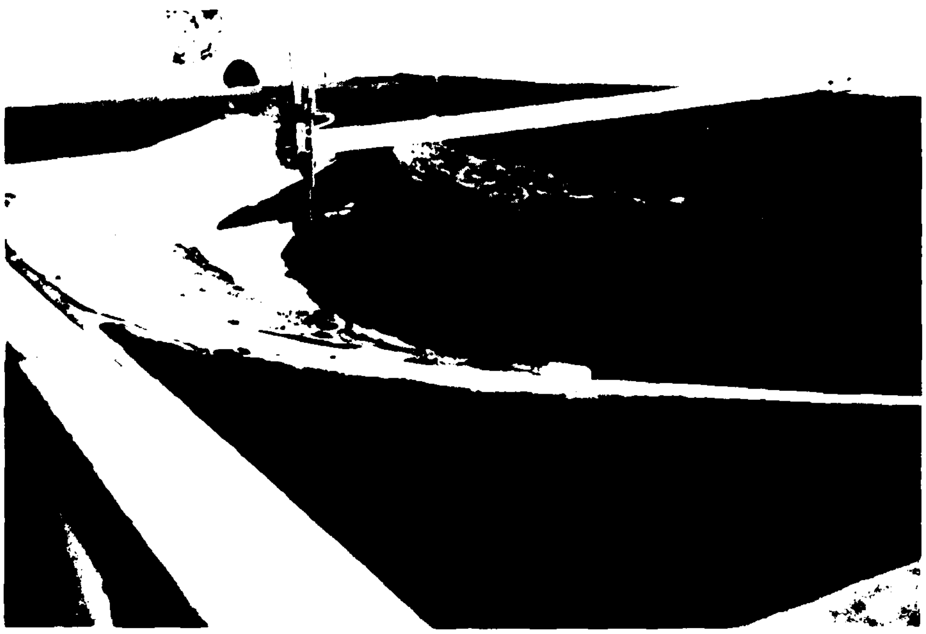


Figure 20. Plan View of Curved Channel Features for 3H:1V Concave Bank (Tests 8 through 14)



A. View Looking Upstream



B. View Looking Downstream

Figure 21. Curved Channel Setup for 3H:1V Concave Bank (Test 14 Conditions Shown).

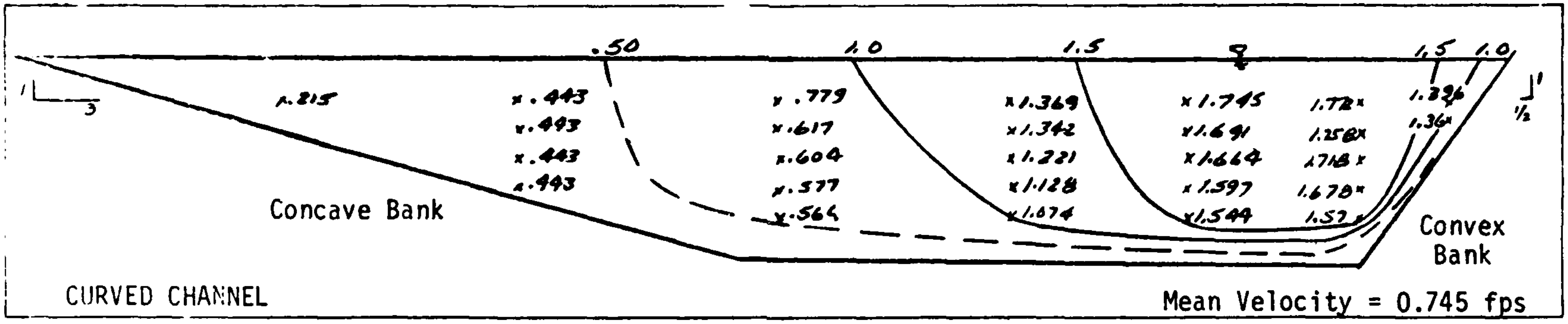


Figure 22. Normalized Velocity Distribution For Test 8.

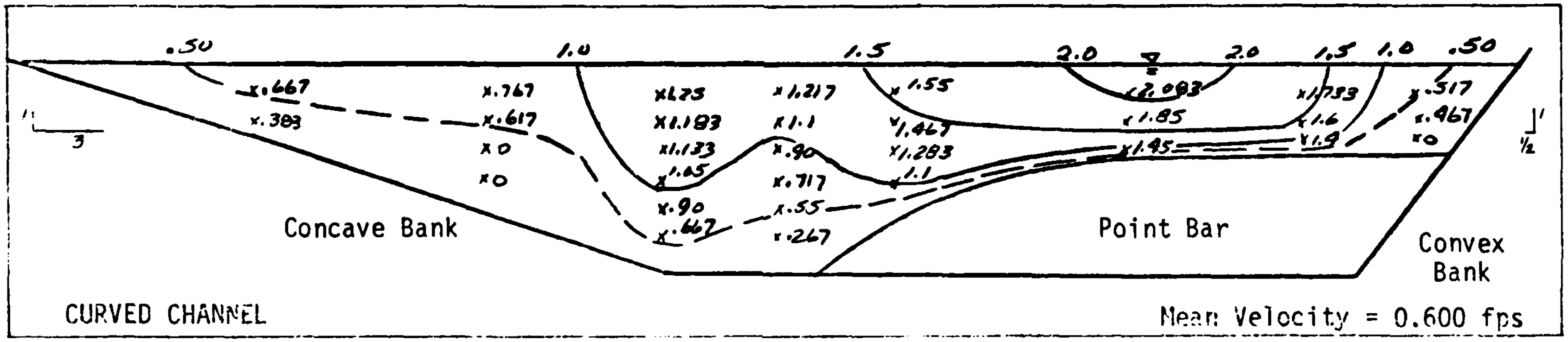


Figure 23. Normalized Velocity Distribution For Test 9.

concave bank. Figure 24 shows the normalized velocities and velocity contours for this test.

Test 11: Local bushy vegetation extending to the toe of the concave bank in the midst of a zone of short vegetation greatly reduced velocities along that bank. Velocities increased near the channel thalweg and the bar due to the resulting flow deflection. An eddy current was present immediately downstream of the coarse vegetation at the concave bank. Bottom currents indicated increased scour of the bed compared to that in Test 10. Sediment transport encouraged downstream extension of the point bar. Normalized velocities and velocity contours are presented in Figure 25.

Test 12: An upstream gravel extension was added to the point bar. This somewhat altered the upstream flow alinement. Hence, flow at the bend was forced further to the outside of the curve. Little effect of short grass on the concave bank was noticed. Figure 26 shows normalized velocities and velocity contours.

Test 13: A further upstream gravel extension to the bar was added. Thick vegetation was added on the bar, with short grassy cover left on the concave bank. Much larger velocities existed near the concave bank than noted in previous tests. Bushy vegetation on the bar, combined with further upstream flow realinement by extension of the bar, forced the flow in the bend toward the opposite side of the channel. The vertical velocity distributions near the bar and the deep central part of the channel showed a zone of higher velocities near the bottom. This

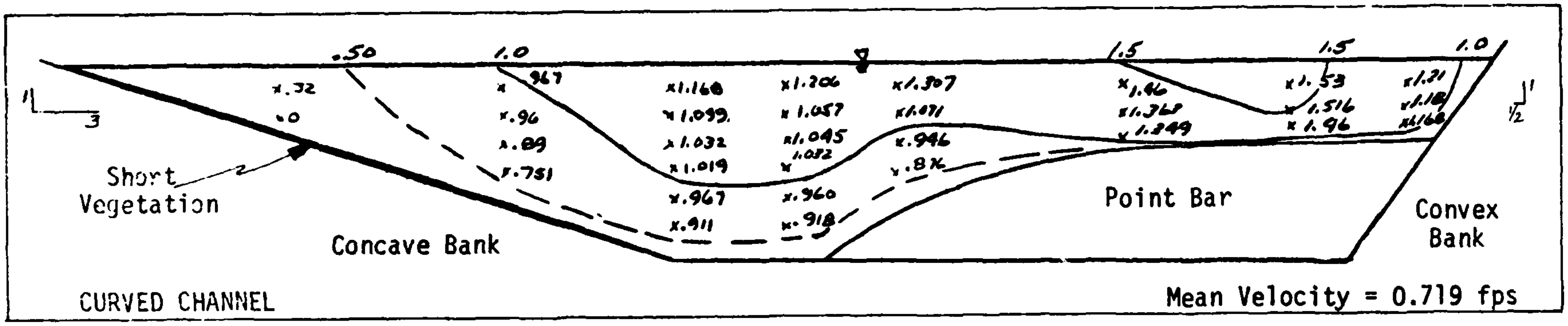


Figure 24. Normalized Velocity Distribution For Test 10.

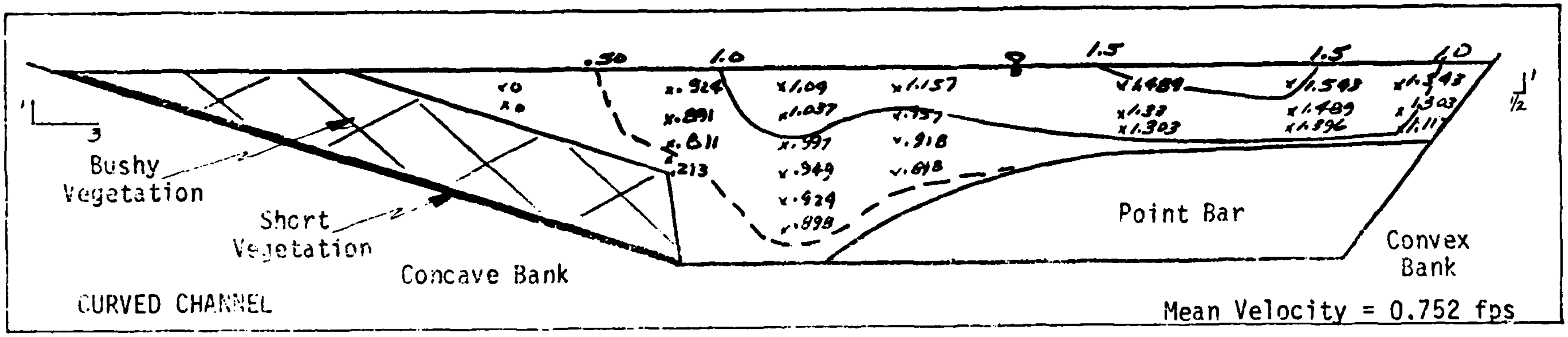


Figure 25. Normalized Velocity Distribution for Test 11.

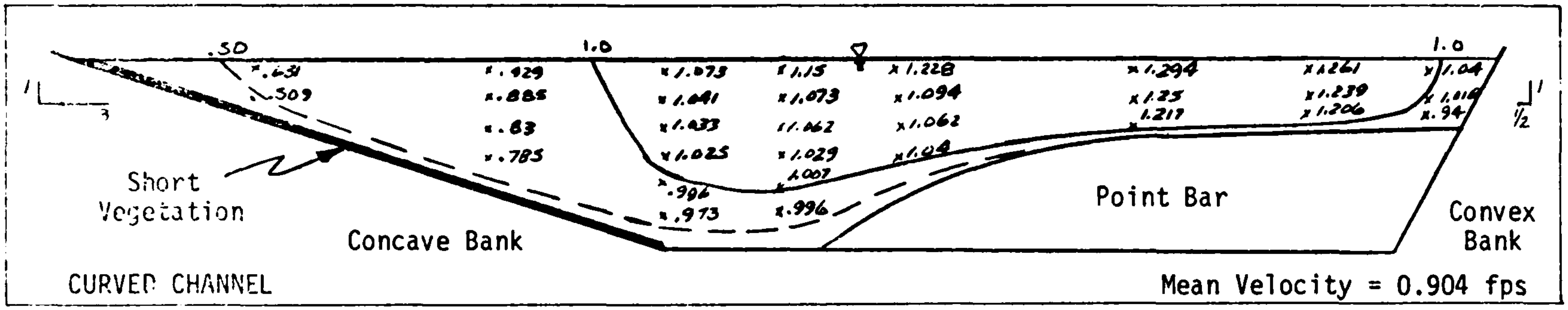


Figure 26. Normalized Velocity Distribution For Test 12.

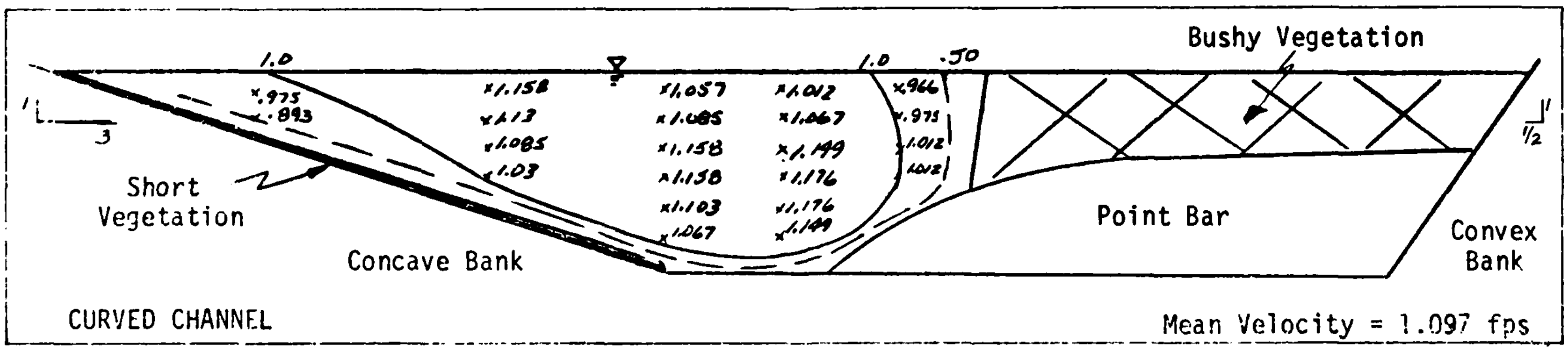


Figure 27. Normalized Velocity Distribution For Test 13.

was evidently caused by the drag exhibited near the water surface by the brush on the bar. Quite high velocities were discovered along the lower half of the concave bank. Due to the blockage of flow over the bar, a potential existed for scour of the bed and the toe of the concave bank. In Figure 27 the normalized velocities and velocity contours are shown.

Test 14: The same effects as those noted in Test 13 were experienced, but they were even more pronounced. The revised channel entrance, simulating a smooth, gradual transition from an upstream bend to the test bend, shifted the intervening crossing somewhat upstream. This resulted in higher velocities to the left of the stream centerline in the bend. Even in this situation, the most adverse case considered for erosion at the 3H:1V concave side slope, weak currents and an eddy effect were noted on the upper concave bank. The flat slope greatly dispersed the high velocities near the concave bank. The vertical velocity distribution near the bar was again indicative of the roughness exhibited by the brush on the bar. Normalized velocities and velocity contours are presented in Figure 28.

Curved Channel With 2H:1V Side Slope at Concave Bank

Tests 15 through 22 were conducted with various channel features as shown in Figure 29. Specific conditions for one of these tests are shown in Figure 30.

Test 15: No vegetation was present for the 2H:1V side slope with point bar. Velocities were fairly uniform in much of the channel. Scour and undercutting of the bank are quite likely, based upon the high

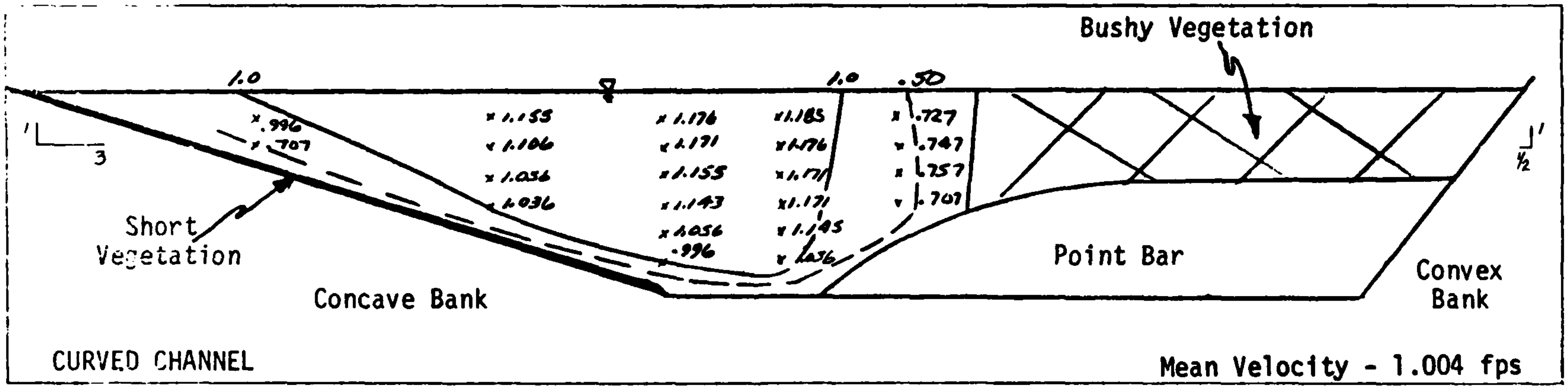


Figure 28. Normalized Velocity Distribution for Test 14.

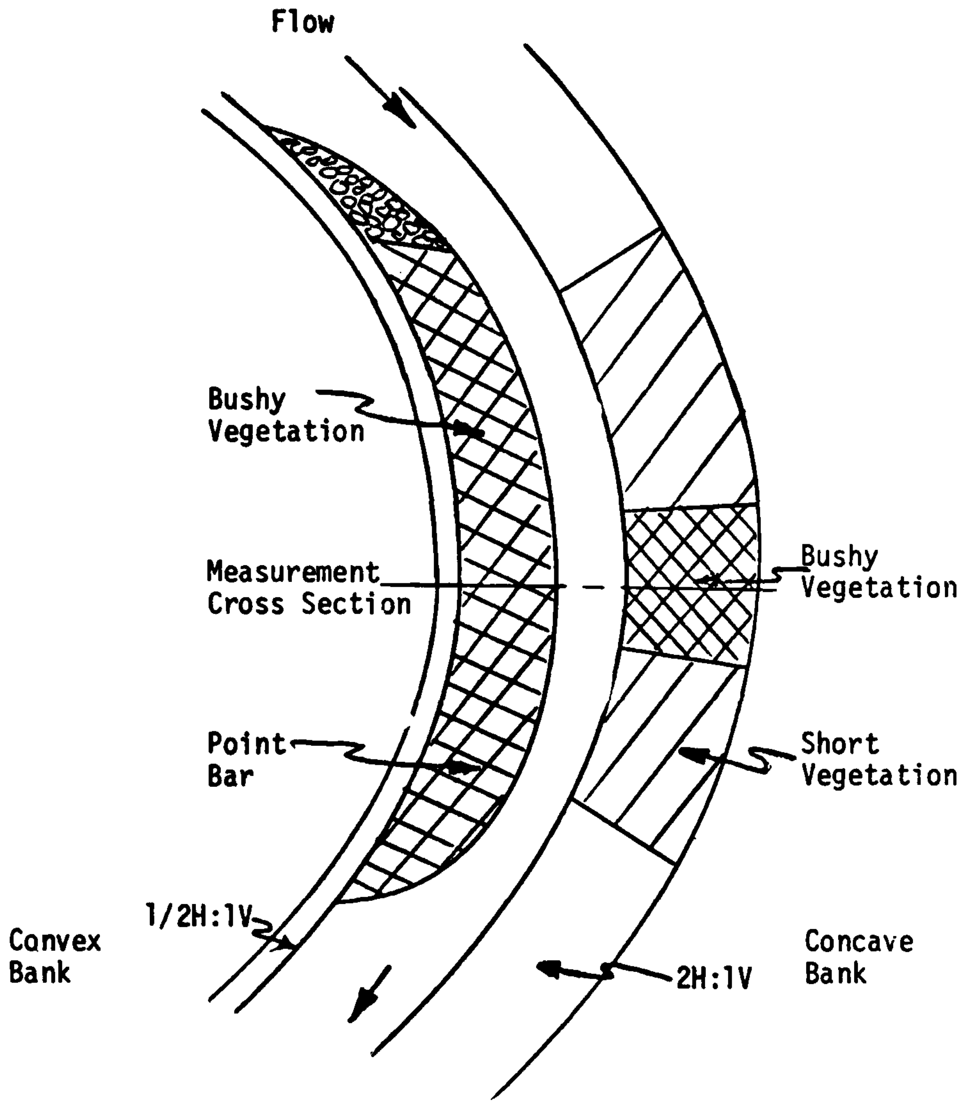


Figure 29. Plan View of Curved Channel Features for 2H:1V Concave Bank (Tests 15 through 22)

A. Flow During Test 22, View Looking Upstream

B. Channel After End of Test 22, View Looking Upstream

Figure 30. Curved Channel Setup for 2H:1V Concave Bank.

velocity and shear stress indicated near its base. The flow over the bar seems to alleviate the problem. Figure 31 shows the normalized velocities and velocity contours.

Test 16: Short vegetation on the concave bank appears to have caused little change in velocity patterns from the bare bank case treated in Test 15. Resulting normalized velocities and velocity contours are shown in Figure 32.

Test 17: Short, grassy vegetation was again simulated on the concave bank and bushy vegetation was added on the point bar. The heavily vegetated point bar caused greatly increased velocities in the channel. during high flow conditions. This is much more serious in the case of the steeper concave bank slope. Erosion and undercutting there are quite possible. The brush also caused larger bottom velocities than surface velocities near the bar. Figure 33 shows the normalized velocities and velocity contours.

Test 18: The short vegetation was removed from the concave bank for this test. In comparison with results from the previous test with such short vegetation, a slight increase of velocity was indicated near the bank due to the reduced roughness. The normalized velocities and velocity contours are shown in Figure 34.

Test 19: A clump of bushy vegetation in the midst of short vegetation on the concave bank resulted in a downstream eddy. Flow was constricted in the deeper channel by the bushy vegetation which extended to the toe of the slope. This resulted in significantly higher velocities there. Bed scour was evident but removal of vegetative cover

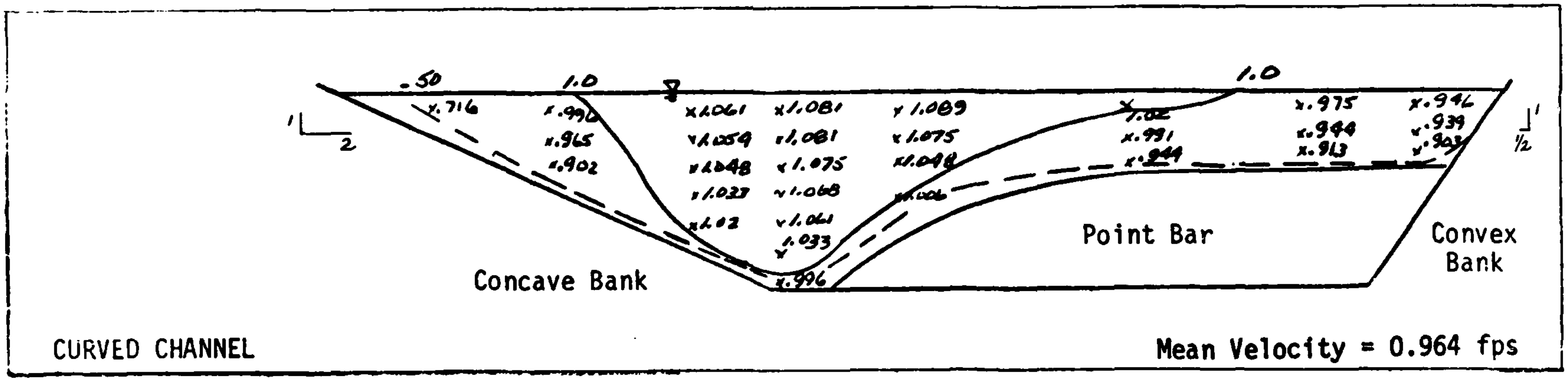


Figure 31. Normalized Velocity Distribution for Test 15.

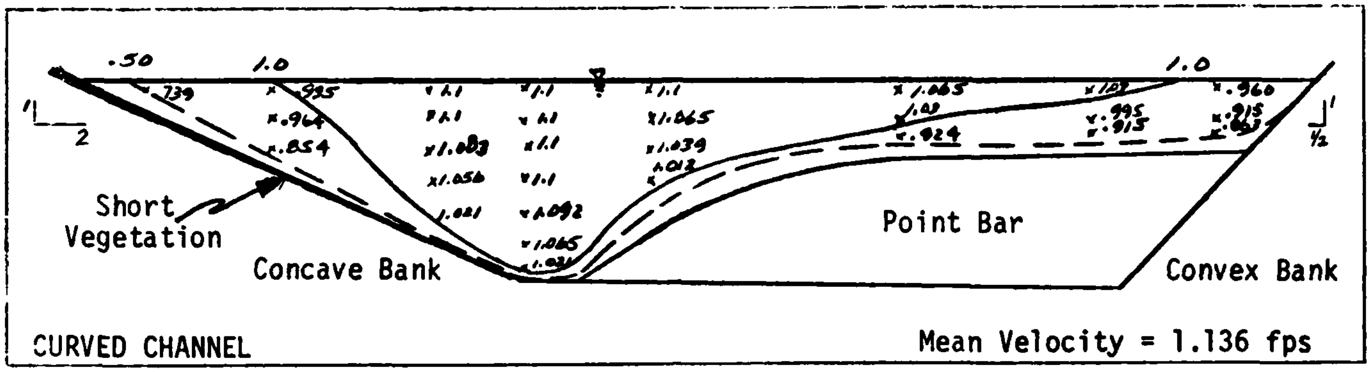


Figure 32. Normalized Velocity Distribution for Test 16.

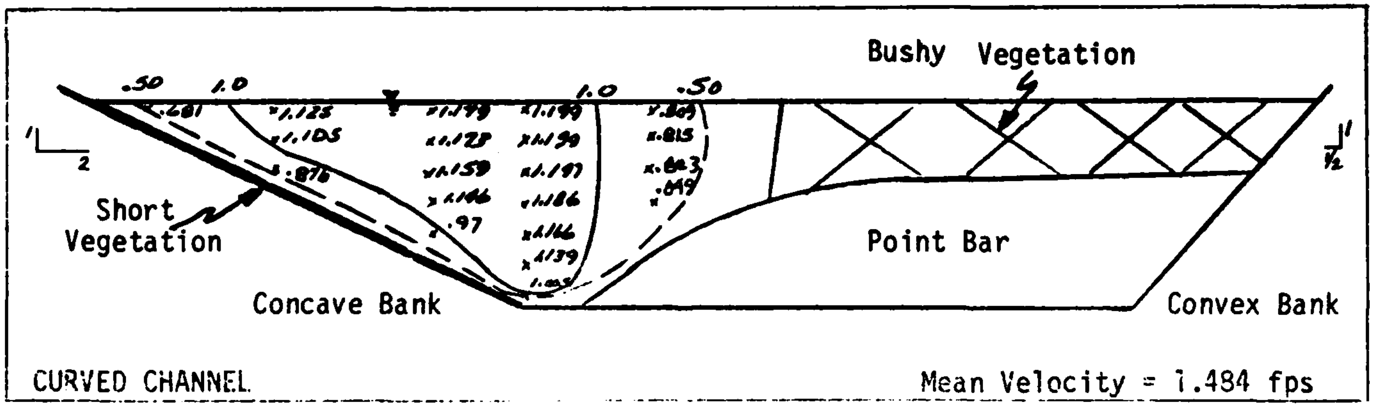


Figure 33. Normalized Velocity Distribution for Test 17.

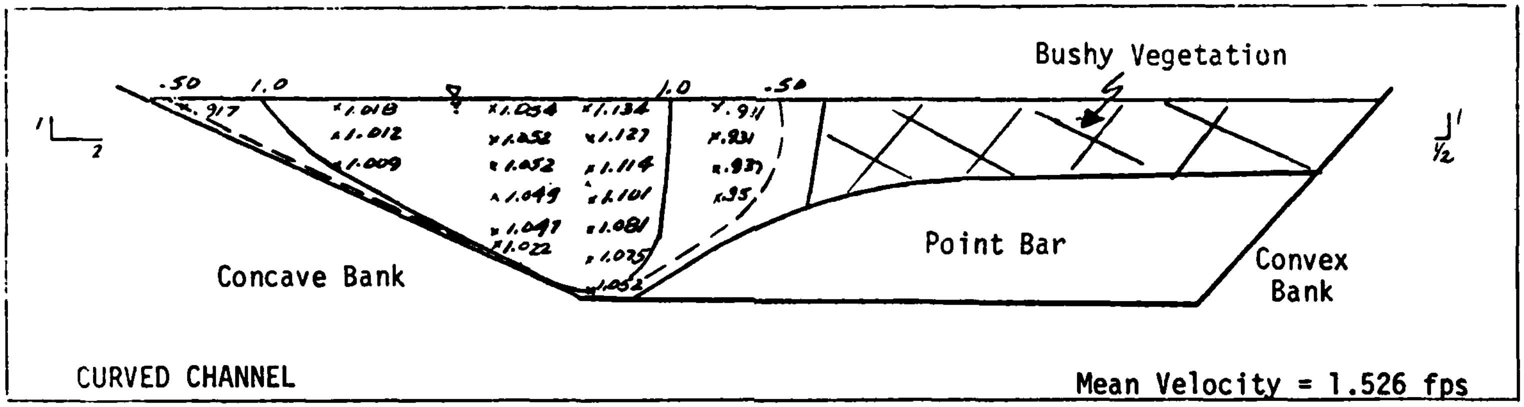


Figure 34. Normalized Velocity Distribution for Test 18.

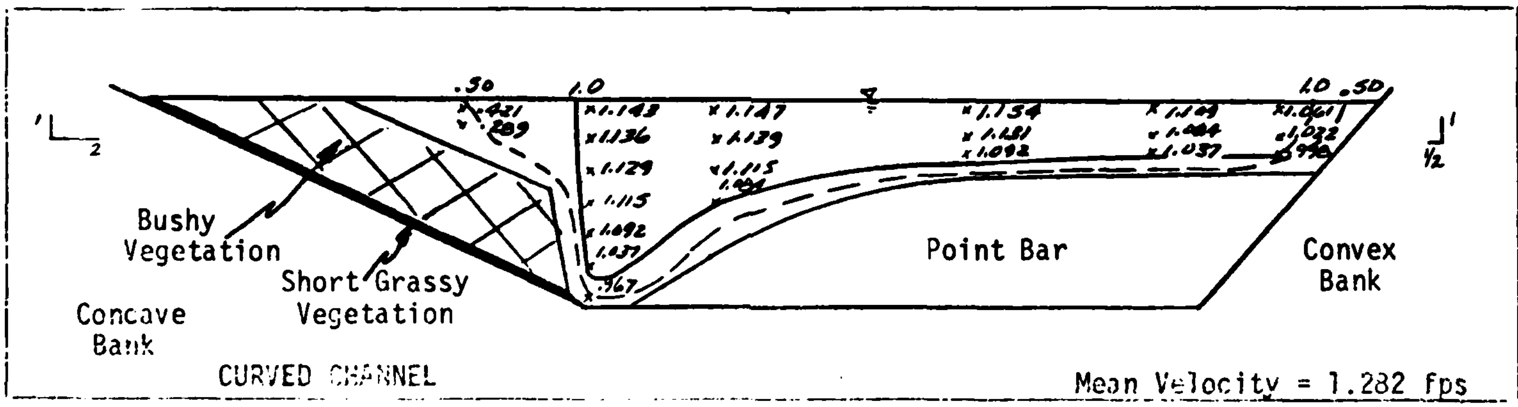


Figure 35. Normalized Velocity Distribution For Test 19.

from the point bar reduced the bed scour from that in Test 18 by allowing flow over the bare bar. Significant bed scour took place directly below the concave-bank vegetation in the deep channel and toe undercutting is almost a certainty there for the simulated conditions. Velocities were reduced higher on the bank in the zone where the brush was placed. Figure 35 shows the normalized velocities and velocity contours obtained.

A supplemental investigation of the effect of the distribution of bushy vegetation on the concave streambank was undertaken at the conclusion of model testing, using the configuration of Test 19. The extension of bushy cover part way and completely down the bank, continuous cover throughout the curve, and alternating bare bank and clumps of vegetation provided several vegetal arrangements for comparative testing. It was found that the amount of extension of the bushy material down the bank into the channel was not critical in reducing the potential scour effect below it on the slope. The high velocities were simply shifted up the slope as the lower boundary of vegetation was shifted up the slope. Patches of vegetation alternating with areas of bare bank induced small eddy effects next to the bare bank areas.

Test 20: Removal of the point bar reduced the velocities on the concave bank, which was covered by short grassy vegetation. Maximum velocities were experienced at the bed near the toe of the concave slope. A relatively uniform velocity distribution could be noted. Little bed scour was found during the study of bottom currents. The normalized velocities and velocity contours are shown in Figure 36.

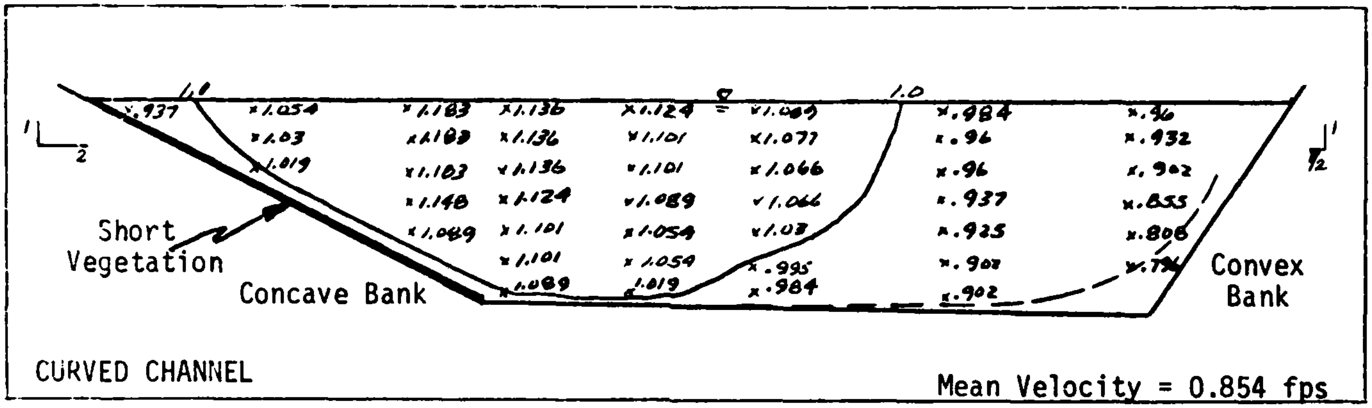


Figure 36. Normalized Velocity Distribution For Test 20.

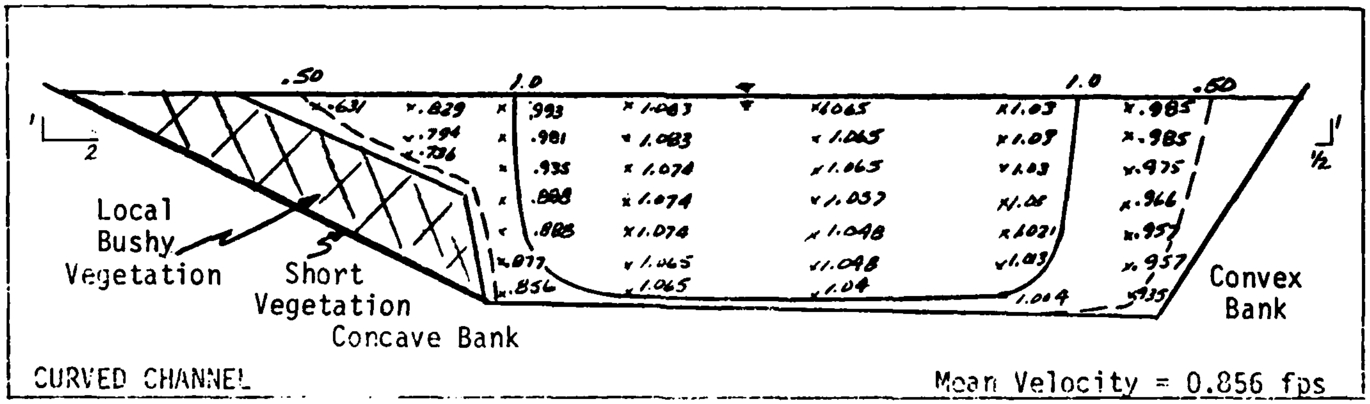


Figure 37. Normalized Velocity Distribution For Test 21.

Test 21: Local bushy vegetal cover was added near the center of the short vegetation on the concave bank. This greatly reduced nearby velocities and shifted the flow somewhat to the inside of the bend. Maximum velocities occurred near the channel centerline. Bottom velocity studies indicated only a slight scour effect at the toe of the concave bank. A small eddy formed downstream of the brushy material near the concave bank. Figure 37 shows the normalized velocities and velocity contours.

Test 22: This test, with no vegetation on the concave bank, showed no significant deviation in results from those for Test 20: the bare bank case and the short grass effect indicate approximately the same results. Figure 38 shows the normalized velocities and velocity contours.

Curved Channel With 1/2H:1V Side Slope at Concave Bank

Tests 23 through 25 were conducted with various channel features shown in Figure 39. Specific conditions for one of these tests are shown in Figure 40.

Test 23: Because no point bar was present and no vegetation was simulated, this channel was symmetrical about its centerline. However, the bend curvature caused the flow to be strongly non-symmetrical. The steep concave bank experienced a large velocity increase nearby and maximum velocities existed near that bank. Bank undercutting was a certainty if this had been an erodible material. Figure 41 shows the normalized velocities and velocity contours.

Test 24: In this test, a point bar was added. The resulting velocities were shifted away from the point bar. Very large velocities

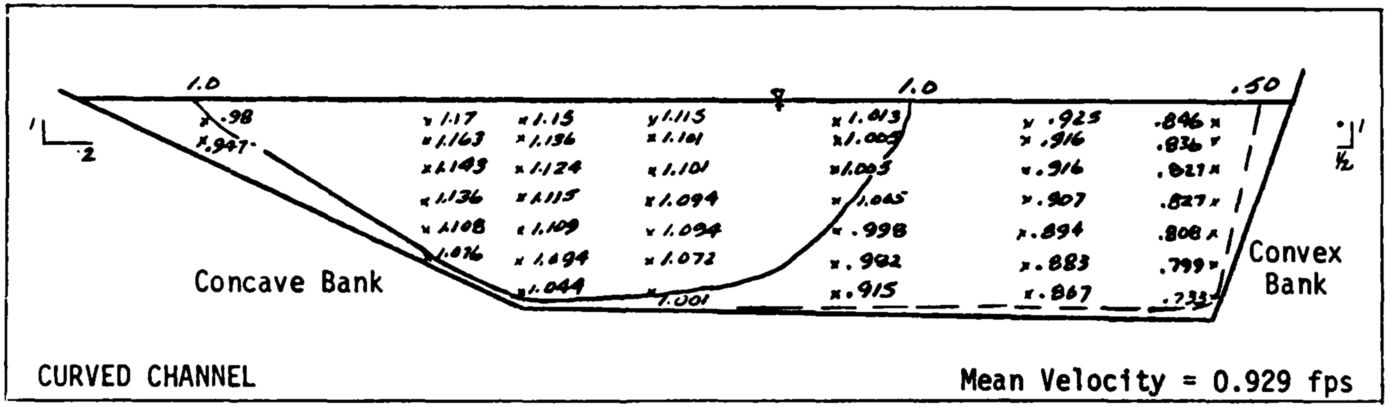


Figure 38. Normalized Velocity Distribution For Test 22.

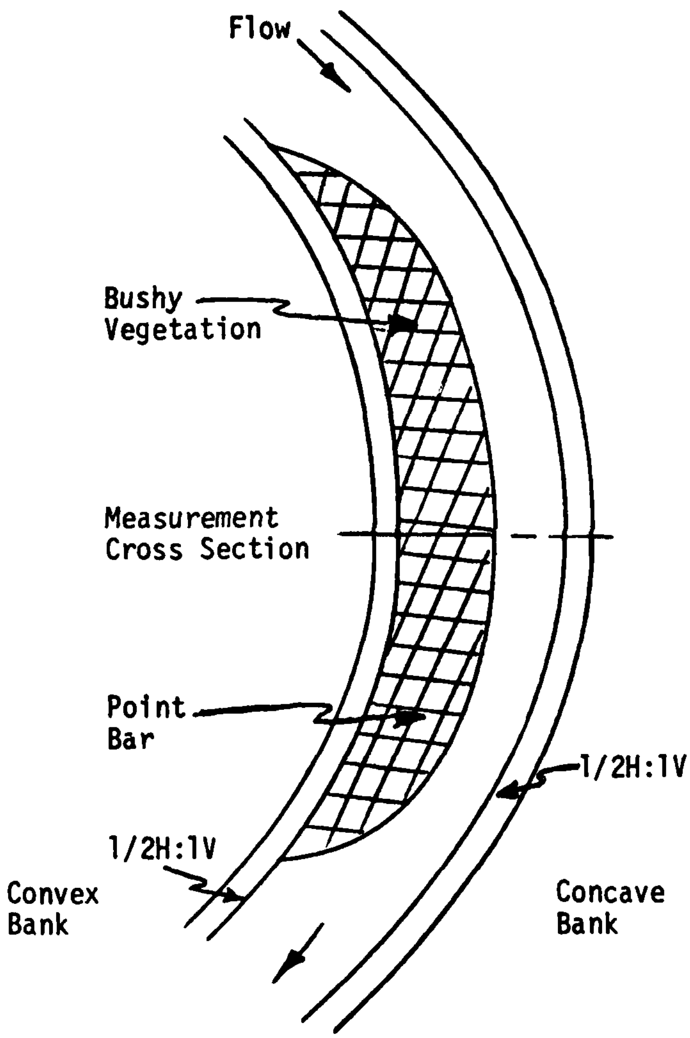
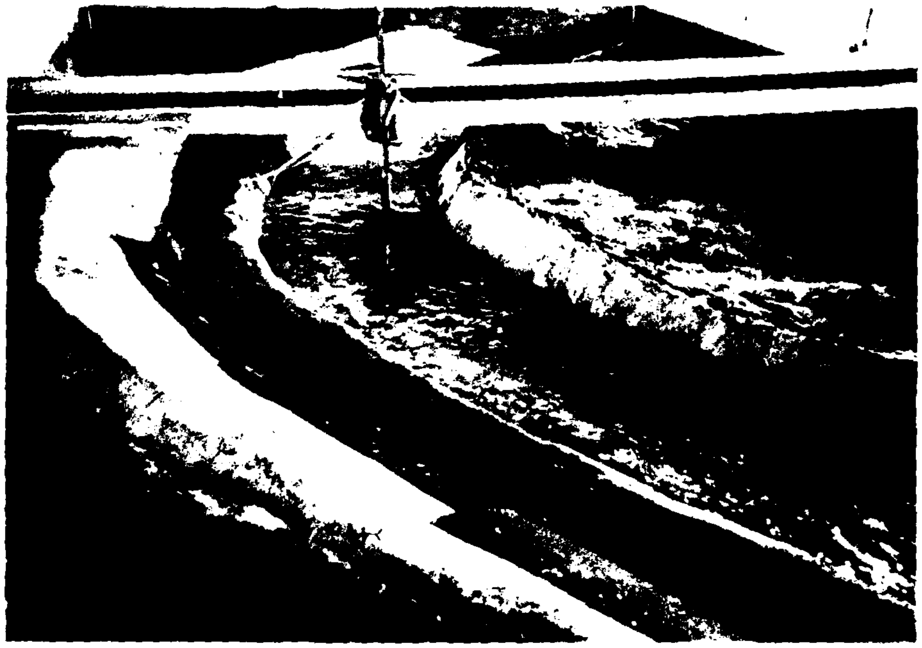


Figure 39. Plan View of Curved Channel Features for 1/2H:1V Concave Bank (Tests 23 through 25)



A. Flow During Test 23, View Looking Downstream

B. Channel Before Start of Test 23, View Looking Downstream

Figure 40. Curved Channel Setup for 1/2H:1V Concave Bank.

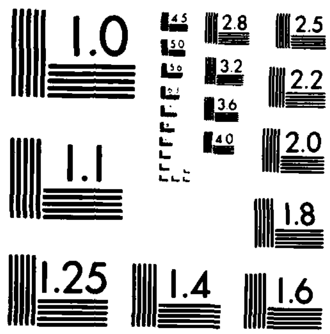
AD-A150 614 WILLAMETTE RIVER BASIN STREAMBANK STABILIZATION BY NATURAL MEANS(U) OREGON STATE UNIV CORVALLIS WATER RESOURCES RESEARCH INST P C KLINGEMAN ET AL. JUN 76 3/3

UNCLASSIFIED F/G 13/2 NL

END

FILMED

DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

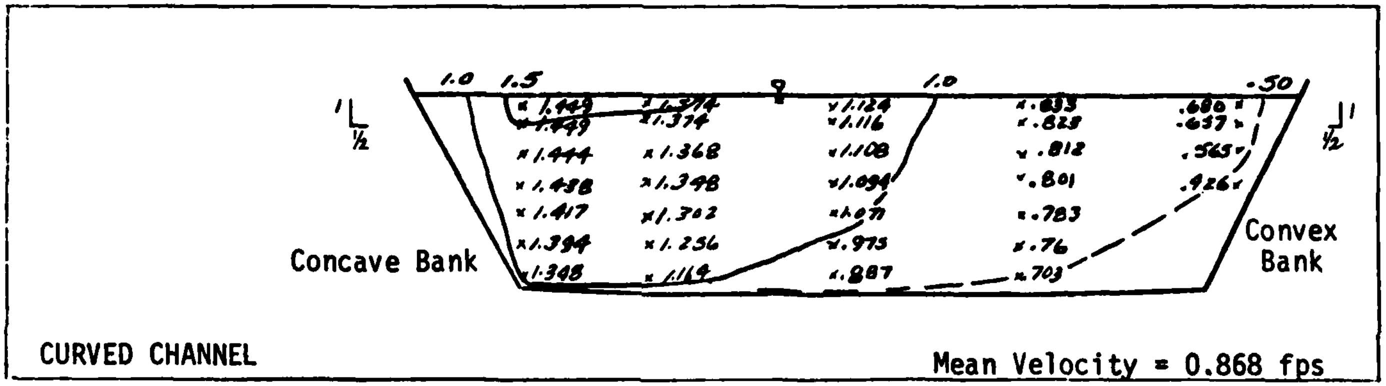


Figure 41. Normalized Velocity Distribution For Test 23.

were also found from the bottom to the surface at the concave bank due to the smaller flow cross section available. Flow over the bar itself involved large velocities. It is a possibility that the bar might be eroded in this configuration if the concave bank is resistant to scour. Appreciable bed scour was evident. The normalized velocities and velocity contours are shown in Figure 42.

Test 25: Thick bushy vegetation was simulated on the point bar. Extremely large velocities (not shown by the normalized values) occurred due to the flow constriction caused by the vegetated bar. This channel configuration exhibited the worst possible scour potential for banks and bed of all the cases tested. Figure 43 shows the normalized velocities and velocity contours.

DISCUSSION AND INTERPRETATION OF RESULTS

The model testing program provided data that permitted the analysis of the effects of side slope, vegetal cover, and channel geometry. Velocity distributions were measured and the surface and bottom currents were observed. An analysis of test data was conducted and interpretations were made of the various different channel effects. Discussion of the individual tests was presented in the preceding section. In this section the general results and interpretations for the entire testing program are discussed. The discussion is divided into two parts: that treating the straight channel and that for the curved channel.

Straight Channel

Studies conducted in the straight channel were made for constant

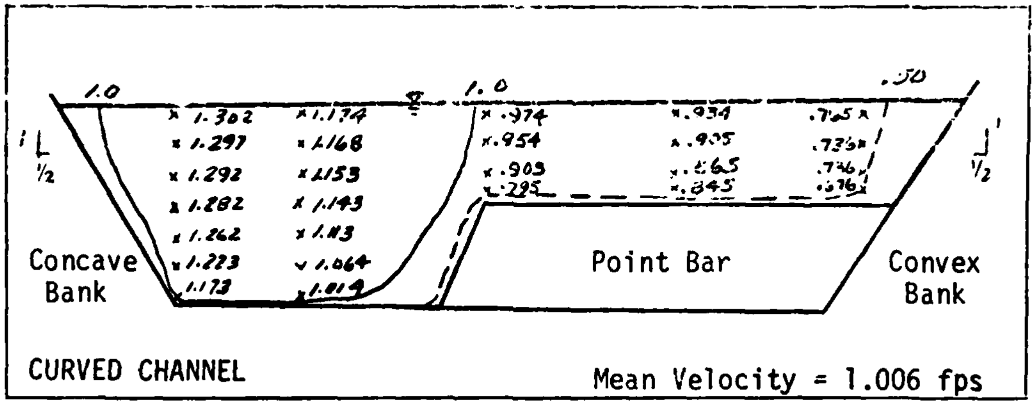


Figure 42. Normalized Velocity Distribution For Test 24.

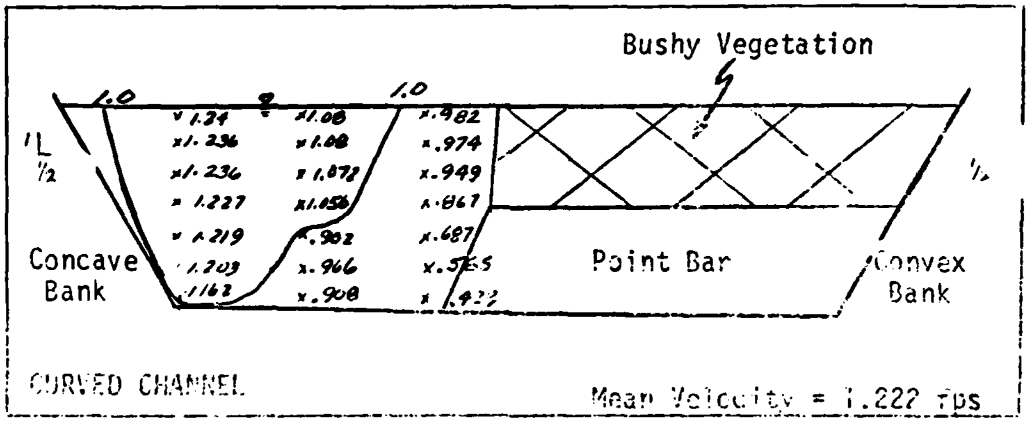


Figure 43. Normalized Velocity Distribution For Test 25.

bank slopes of 2H:1V. Therefore, the only test variable for this geometry was the extent of simulation of vegetal cover.

Short vegetation had slight effect on the flow in comparison with bare banks. This was indicated by a small increase in channel roughness. Velocities adjacent to the burlap material were slightly less than those in the case of a bare bank. Aside from this benefit, it seems unlikely from laboratory data that short, grass-like vegetation will cause a sufficient increase in bank roughness to deflect potential scour velocities. The principal advantage of such vegetation may be in its ability to hold the soil surface together by means of its root structure.

The hydraulic effect of the loss of vegetal cover from one bank of a grass-lined straight channel is shown in Figure 44. The existence of short vegetation on both banks resulted in a symmetrical velocity distribution about the centerline of the channel. When vegetation was removed from one bank, the velocity distribution shifted slightly towards the bare bank and a small increase in velocities near the bank was observed.

The effect of bushy vegetation was much more significant. Testing for this configuration showed that some channel constriction occurred when both banks had this vegetal cover. Velocities were correspondingly greater in this channel cross section than either upstream or downstream. Brush effectively screened the channel banks from the flow by acting as a thick buffer layer. Therefore, even though average and local velocities were greater in the constricted waterway, the bank received lower shear stresses.

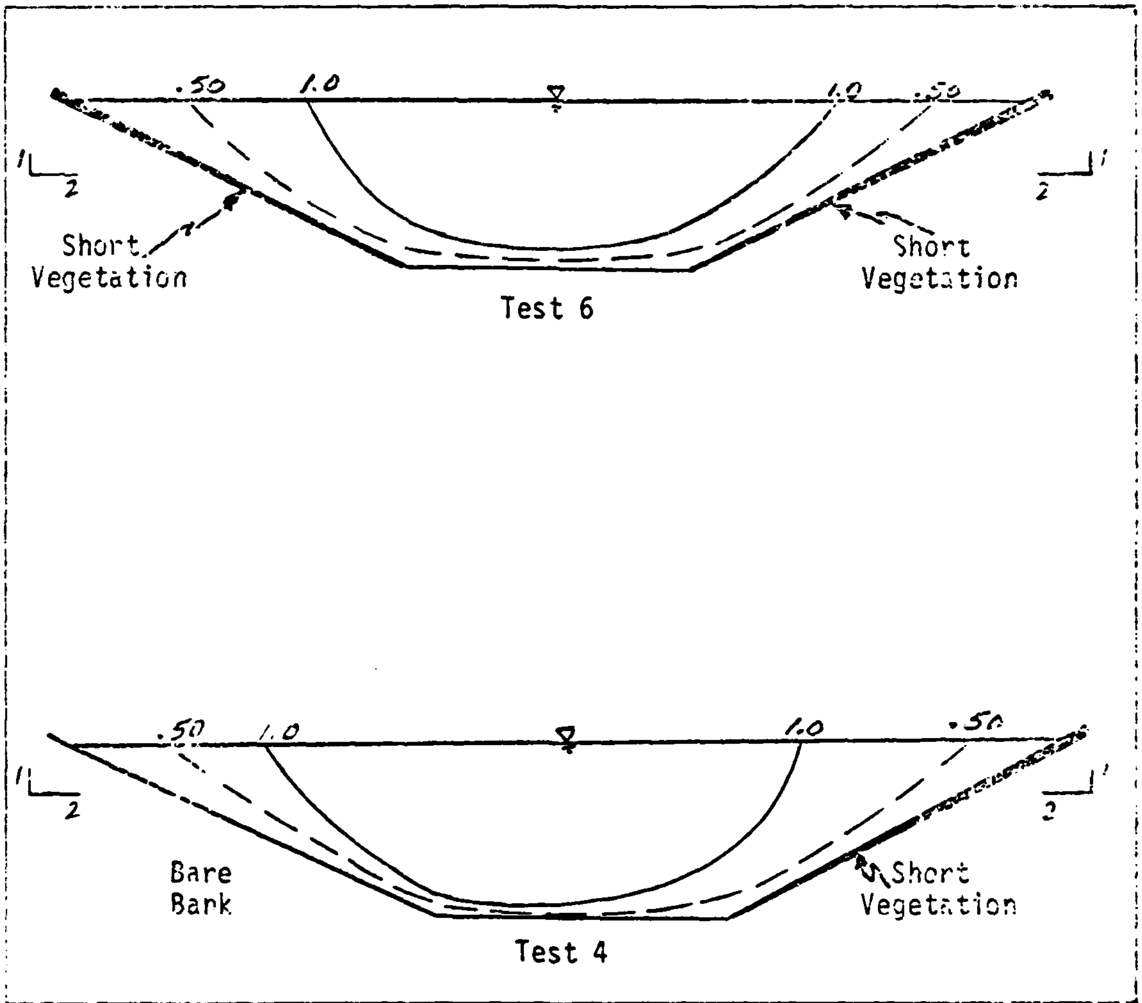


Figure 44. Hydraulic Effect of Loss of Vegetal Cover From One Bank Of A Grass-Lined Straight Channel.

Thick, bushy vegetation placed on only one bank also had a marked effect on the velocity distribution. Shear stresses on the protected bank were diminished by the vegetal buffer zone. Higher velocities were recorded along the opposite, unprotected bank. Dependent upon channel width, this indicated that a thick buffer zone on one bank could increase the scour potential on the opposite bank.

Figure 45 shows the relative magnitudes of the hydraulic effect of various vegetal covers existing only on one bank. The velocity distribution was quite symmetrical in the channel when both banks were bare. The addition of short vegetation on the right bank resulted in a minor shift of the velocity contours towards the opposite bank. (Bushy vegetation, when added to one bank just upstream of the test cross section, caused a large shift of the velocity distribution toward the bare bank.) (An eddy formed on the same bank, downstream of thick, bushy vegetation. (This was similar to those observed downstream of many revetments.)) Evidently a scour potential exists downstream of thick clumps of brush due to such flow disturbances. Another similar problem could arise in the case where bushy cover is interrupted and not a continuous blanket. This might be caused by a failure to adequately maintain the bank vegetation. Bare spots near thick cover seem to be subject to the erosive action of local eddy currents. Such brush patterns were not simulated in the experimental work but the eddy effect downstream of thick cover appears to substantiate the possibility.

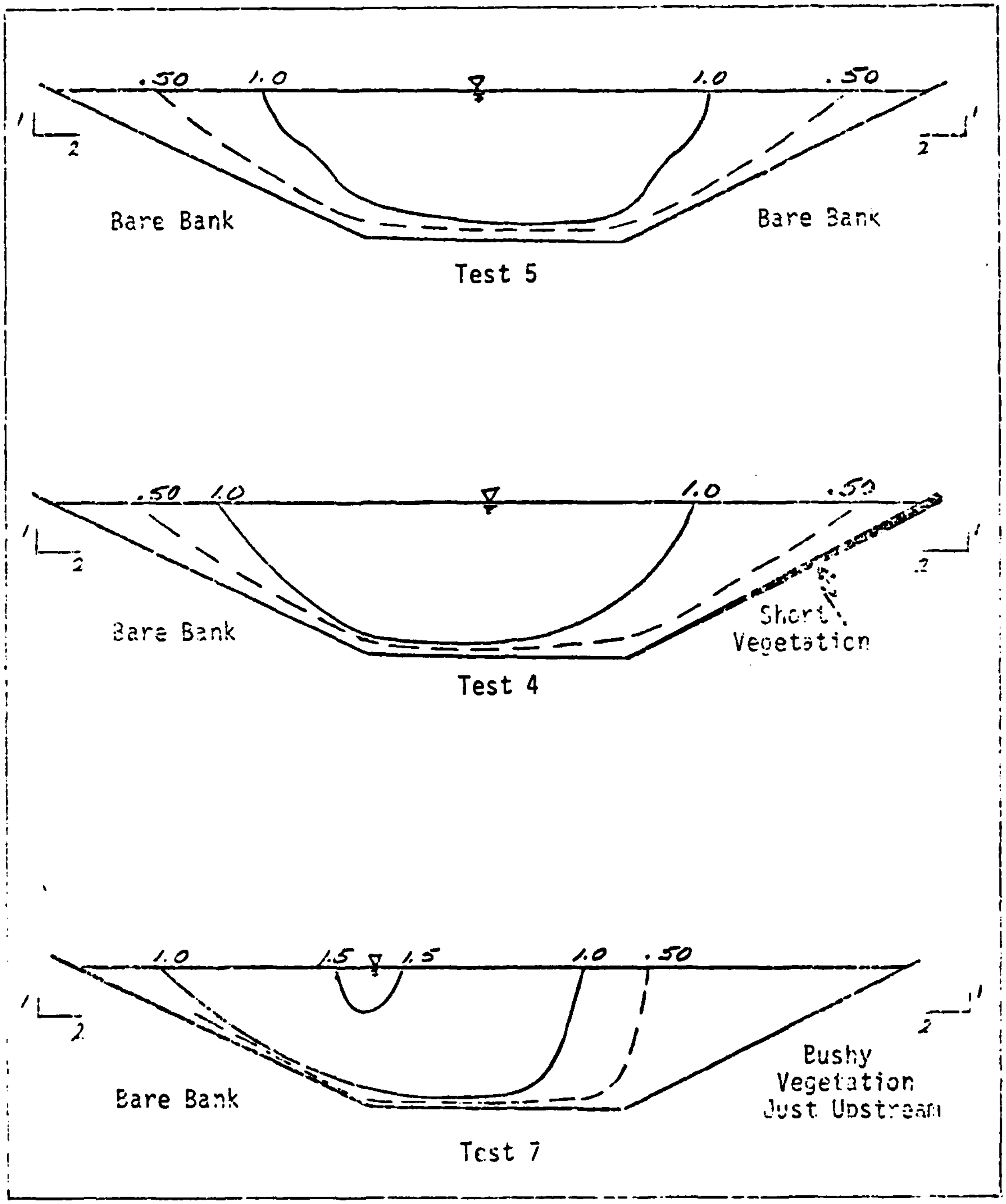


Figure 45. Hydraulic Effect of Various Vegetal Covers at One Bank of a Straight Channel.

Curved Channel

Parameters that were varied in testing the curved channel included concave bank slopes, vegetation, and upstream flow alinement related to abruptness of upstream curve reversal. Many combinations of these variables were considered. Several interesting interpretations of test data are possible due to the numerous channel configurations tested.

Side slope was one of the most important factors in determining local velocities. The effect of concave bank slope for identical upstream flow alinement is shown in Figure 46. The 3H:1V slope was so flat that very low velocities were present along the concave bank, regardless of the flow alinement. Even for the most extreme case in which the vegetated point bar blocked half of the high water channel, an eddy formed on the upper part of the concave bank in a zone of low velocity and flow reversal. When the concave bank side slope was increased to 2H:1V, velocities adjacent to that bank were significantly larger. Any combination of vegetal, cross-sectional, and side slope effects was much more critical for the 2H:1V bank than for the flatter bank in producing potentially scouring velocities. The 1/2H:1V sloping of the concave bank will result in scour there regardless of controls placed on the other test variables. This was shown by the high velocities near the bare concave bank even when the point bar was removed from the channel (Test 23, shown in Figure 41).

Vegetation simulated on the concave bank was one of the major parameters examined in the study. A comparison of velocity distributions for the non-vegetated concave bank and two vegetated cases are shown in

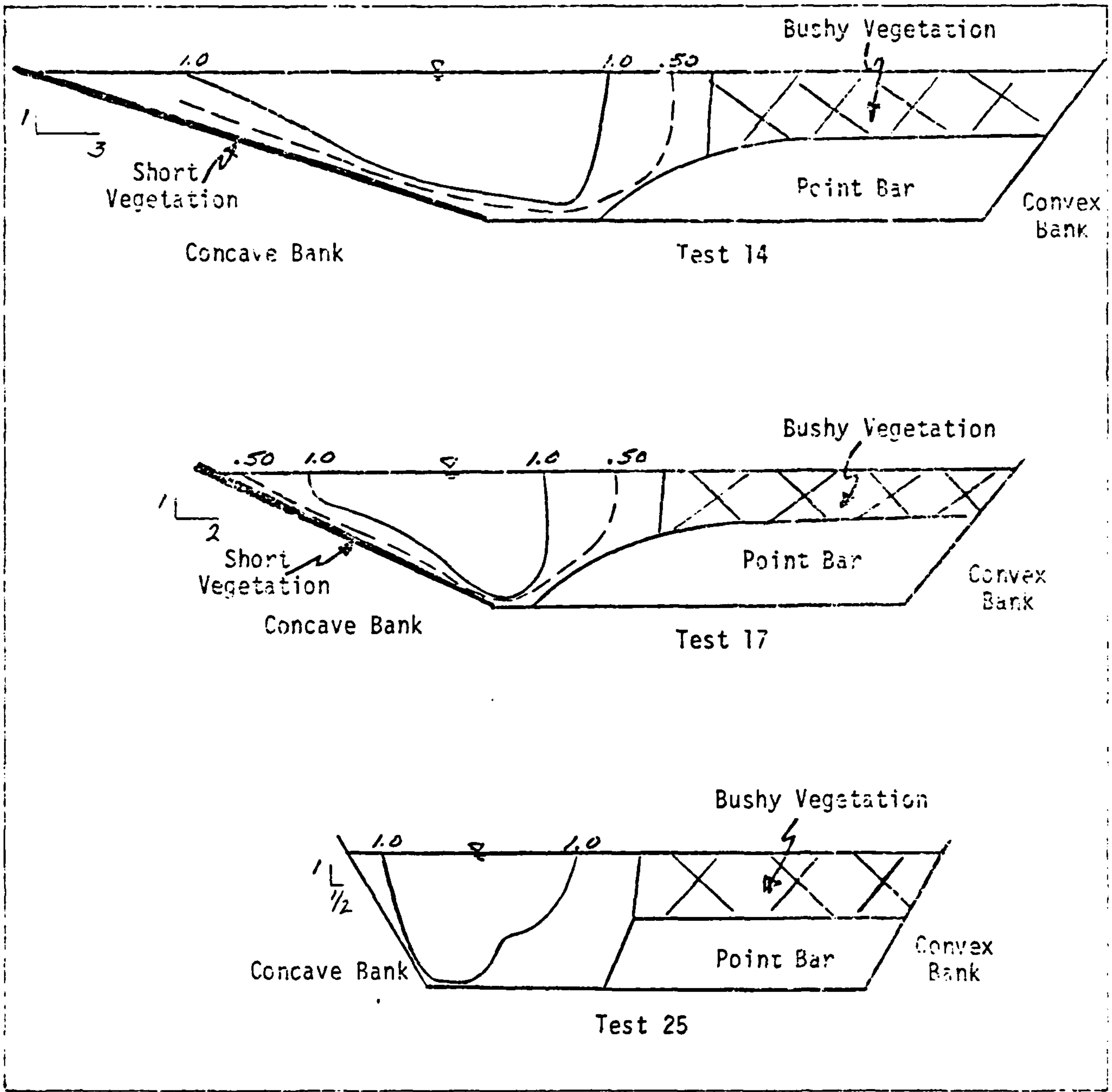


Figure 46. Hydraulic Effect of Bank Slope for a Curved Channel with a Vegetated Point Bar.

Figure 47. Bushy vegetation greatly increased the hydraulic roughness of the concave bank and reduced nearby local velocities. This effect of short vegetation was small, however, such that other parameters would be more influential in determining erosional characteristics.

Long, bushy vegetal cover was more critical than short cover in it's effect on local velocities. Several effects were noticeable. Flow velocities were increased in the deeper section of the channel when such vegetal cover occurred on the point bar or on the concave bank opposite the point bar. Velocities were increased toward the channel center as the flow deflected off of the brushy vegetation. For bushy vegetation on the concave bank, this occurred both when the bar was in place and when it was removed. (Very high velocities were noted at the toe of the concave bank below the vegetation. High velocities were observed directly below the vegetation even when it was raised above the toe to the low water line.) Eddy currents formed downstream of the brush near the bank. In the situation where patches of thick vegetation were alternated with areas of bare bank, eddy effects were experienced at each of the bare bank areas. These currents encourage local streambank erosion. The effects noted above were evident in all test cases but were greatly increased by a vegetated point bar. The vegetated bar appears to be one of the critical considerations, as will be discussed later.

The hydraulic effect of differing upstream flow alinement was critical, as illustrated in Figure 48. The channel entrance and upstream bar extension were manipulated to vary the flow alinement entering the bend. (Velocity distributions indicate that high flows will occur near the

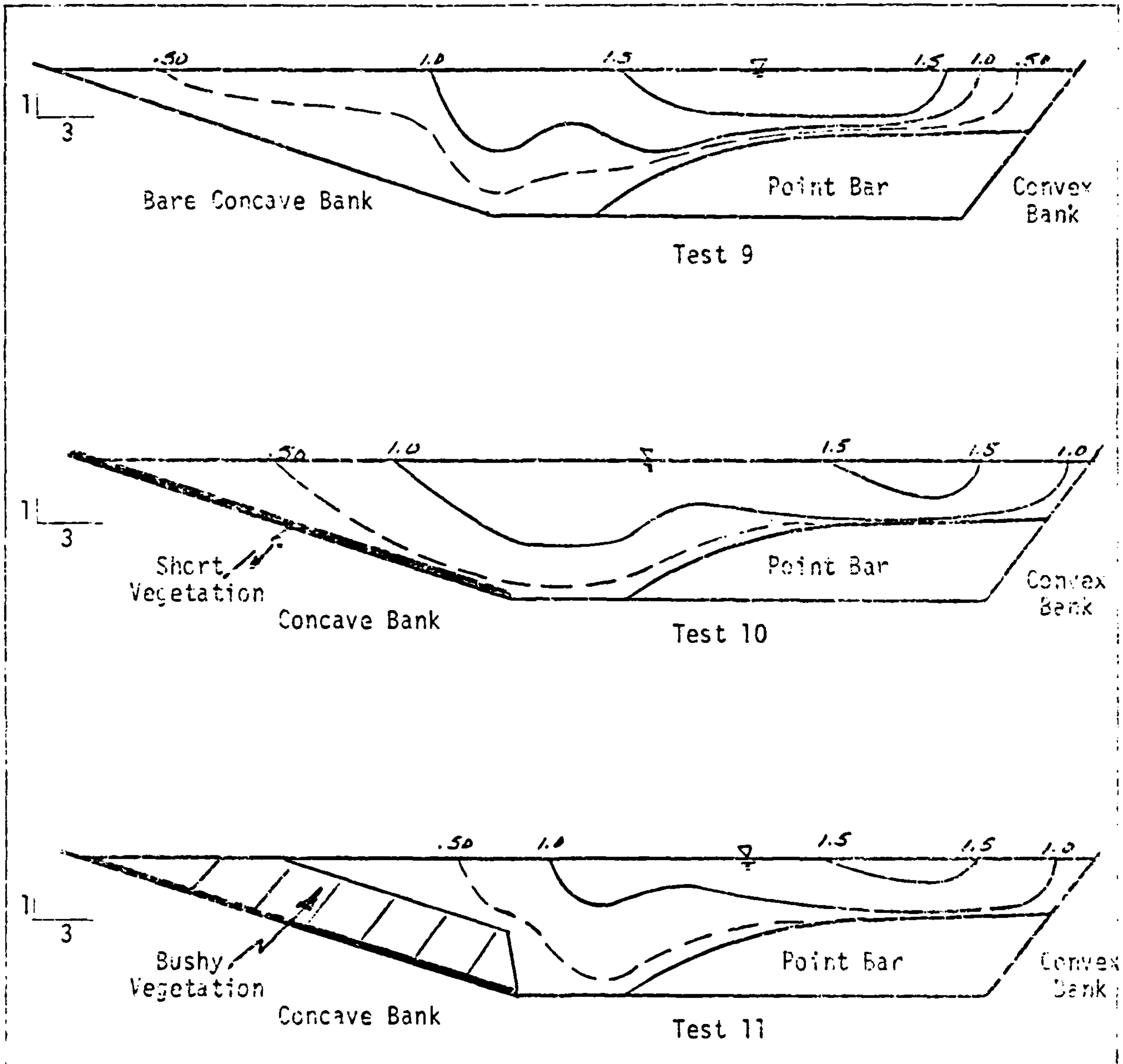


Figure 47. Hydraulic Effect of Vegetal Cover on the Concave Bank for a Curved Channel with a Bare Point Bar and a Sharp Upstream Curve Reversal.

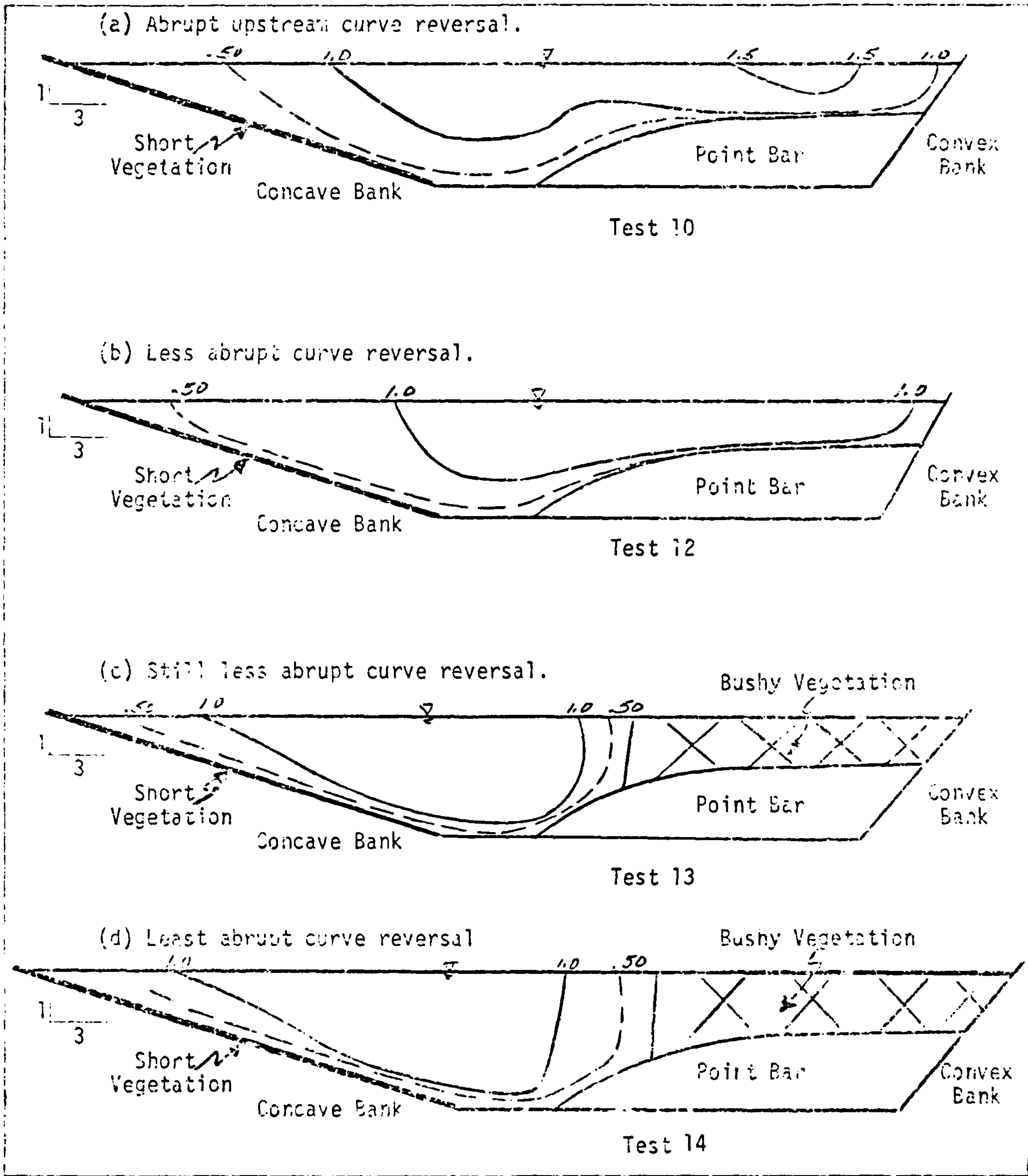


Figure 48. Hydraulic Effect of Degree of Upstream Curve Reversal.

convex bank for a sharp, abrupt upstream curve reversal. When the upstream curve reversal was not as abrupt, the flow contours shifted through a longer crossing between bends before moving outward toward the concave bank at the test bend. The most critical case considered, as far as the concave bank was concerned, dealt with a fully developed upstream crossing together with a vegetated point bar condition. Quite high velocities adjacent to the concave bank were observed and the velocity distribution indicated that the majority of flow passed near that bank.

The influences of point bars and upstream flow alinements are shown in Figure 49. Large discharges caused a more severe scour potential at the concave bank with the point bar present than with it removed; the removal of the point bar shifted the main thread of flow away from the concave bank. In most of the laboratory studies removal of the point bar was significantly beneficial in the relief of erosion potential at the concave bank. However, this was not always very evident or significant. Figures 49 (a) and (b) show the situation for a gradual upstream curve reversal and flow alinement favoring flow toward the concave bank of the test bend, where it is resisted by both short and bushy vegetation. In this case, removal of the point bar had limited benefit in relieving velocities at the concave bend.

Heavily vegetated point bars appear to be an important cause of erosion at the concave bank and bank toe. This was demonstrated by the laboratory tests shown in Figure 50, where a thickly vegetated bar deflected the streamflow significantly toward the concave bank. Additionally, heavy point bar vegetation acted as a channel constriction at high

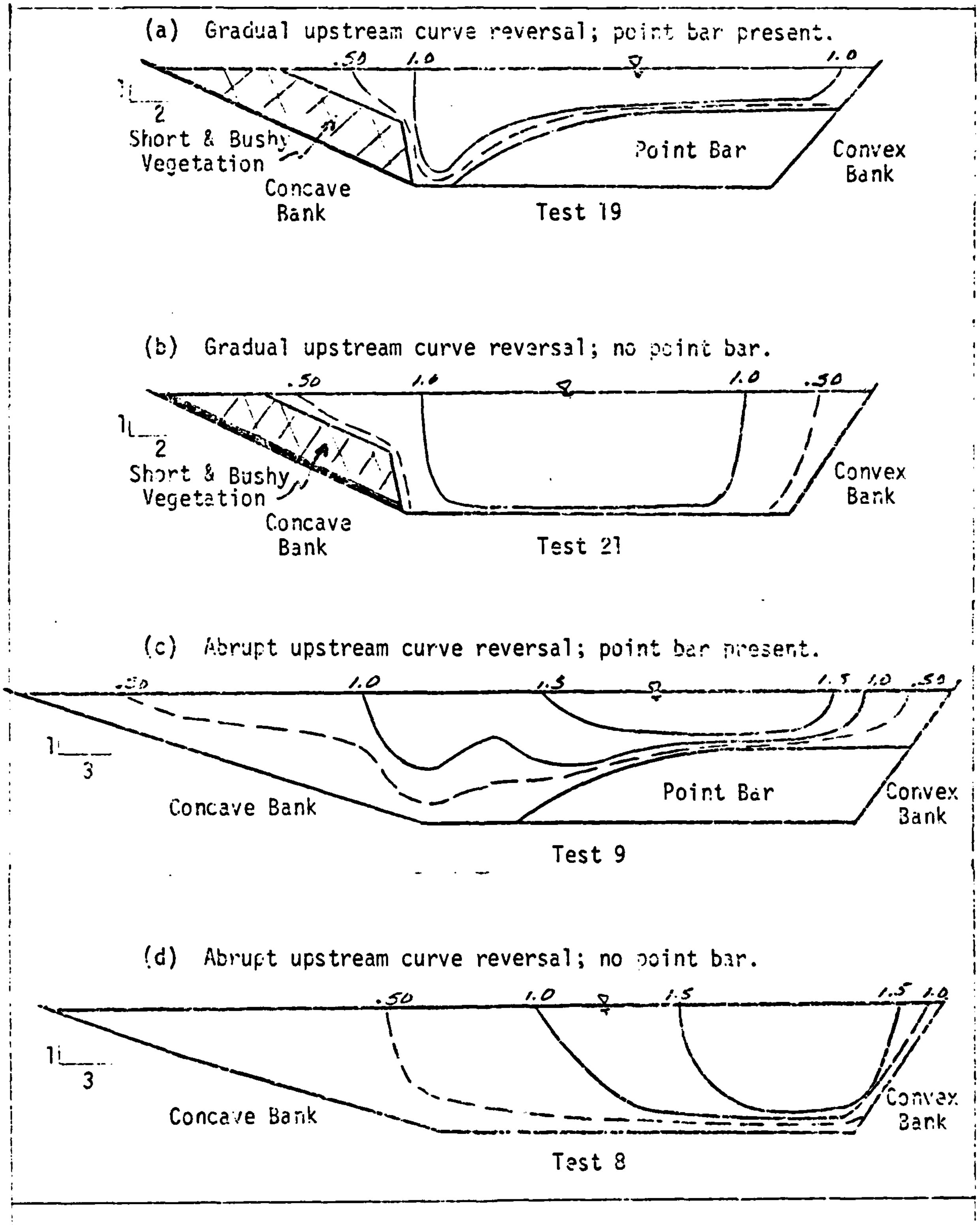


Figure 49. Hydraulic Effect of Removal of a Point Bar for a Curved Channel with Sharp and Gradual Upstream Curve Reversals.

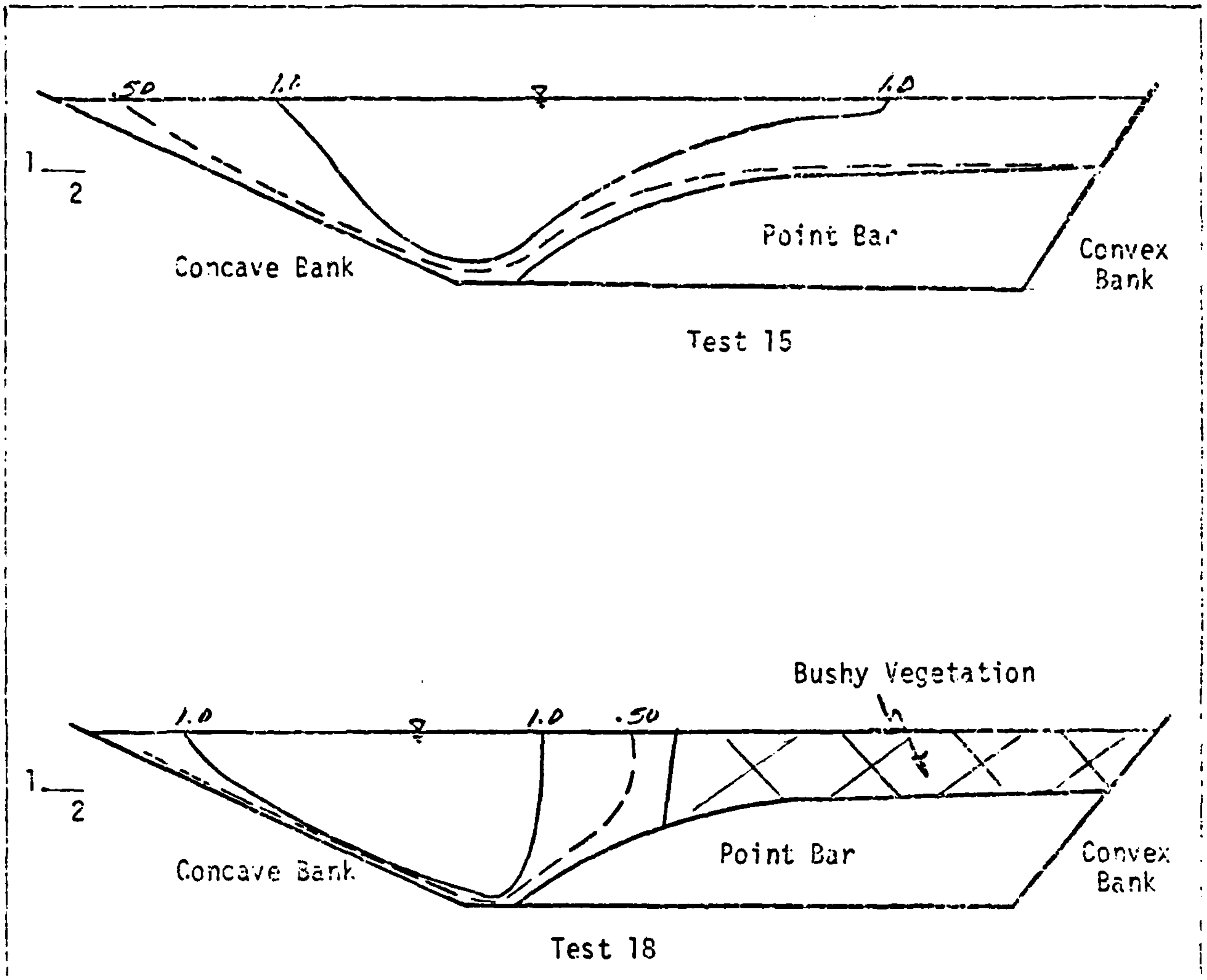


Figure 50. Hydraulic Effect of Point Bar Vegetation for a Curved Channel.

flows by blocking flow that might otherwise occur across the bar. In all cases, a vegetated point bar resulted in increased local velocities near the concave bank. This influence of vegetated bars was generally negated in the case of the flat 3H:1V concave side slope, where there was a slight velocity effect at the toe of the slope but insignificant effects higher up the bank.

Study of the channel bottom and surface currents allowed several observations to be made regarding secondary currents and streambed scour. All studies were conducted while the point bar was present. A slight amount of scour occurred opposite the bar, in the deep channel, for the 3H:1V concave bank slope. The point bar extended itself downstream through sediment deposition as a result. The 2H:1V slope acted as a stimulus to bed scour below the toe of the bank. Brush on the bar increased bed scour. Brushy vegetation on the concave bank created the worst case of bed scour. For this slope the point bar noticeably extended downstream due to sediment deposition. Deposition also took place along the concave bank downstream of the bushy cover on that same bank.

CONCLUSIONS

Through this model study, data were obtained that allow several important interpretations concerning the usefulness of bank shaping and natural means of bank stabilization. Any set of tests such as these, in which a river has been simulated in a model, tend to neglect many of the real effects that occur in the river. However, the data lead to several qualitative but reasonable conclusions.

Conclusions for Straight Channels

(1) A 2H:1V concave side slope is probably subject to local erosion due to channel irregularities and toe failure rather than being subject to large-scale bank caving.

(2) Short grassy vegetation will be of small help in deflecting flows to retard erosion although its role in providing a root matrix to hold the soil may be significant (this was not studied in the laboratory).

(3) Bushy vegetation will protect the bank in the zone on which it is growing. Relatively narrow channels for which only one bank is vegetated may be subject to scour at the bank opposite the vegetation.

(4) Eddies may occur at the downstream end of bushy vegetal cover, causing local scour along the bank there.

(5) Bushy vegetation should be maintained as a continuous cover. If it is spotty or interrupted, scouring of unprotected areas around such clumps is likely to occur.

Conclusions for Curved Channels

(1) The slope of the concave bank was found to be a very important parameter in controlling bank scour. A 3H:1V slope experienced only moderate velocities. These could produce some scour at the concave bank toe under adverse flow conditions (e.g., with a heavily vegetated point bar). The 2H:1V bank slope was indicated to have a potential for relatively severe scour and undercutting during high-stage flows and with a point bar present at the convex bank. A 1/2H:1V side slope was indicated to be potentially subject to extremely severe erosion over much of its height and particularly at its base.

(2) Short grassy vegetation will provide negligible relief from large near-bank velocities.

(3) Bushy vegetation on the concave bank, if it is maintained, will provide an effective buffer zone. Eddy currents and related local scour are a problem along the bank downstream of this type of vegetal cover. Spotty cover will also cause local scour in adjacent non-vegetated regions.

(4) A point bar always tends to increase the magnitude of erosion on the opposite concave bank. Removal of the point bar had a beneficial effect in situations where the upstream flow alinement favored the flow's following a mid-channel or convex-side alinement through the bend but had little effect in situations where the upstream flow alinement favored a flow direction toward the concave bank of the bend.

(5) Vegetative management on point bars is extremely important. From laboratory tests, a vegetated bar was found to greatly increase the local velocities and scour potential on the concave bank opposite and downstream from the bar.

(6) Scour of the channel bed is most likely to be severe in the case of thick vegetative cover protecting the concave bank. Scour at the toe of that bank is also critical. It appears that a vegetated point bar also increases local bed load transport and bed scour in the deep channel.

(7) In all cases tested, the point bar was extended downstream by sediment deposition there. The greatest bar extensions were evident when the bar was vegetated and a large eddy resulted near the downstream tip of the bar.

(8) When thick vegetative cover was present on the concave bank, some sediment deposition took place immediately downstream on the same side of the channel. It is postulated that this type of situation could produce perturbations in the flow downstream and possibly even lead to the bar formation.

(9) The alinement of flow approaching a bend from upstream was found to exert an important influence over the effectiveness of shaping and managing vegetation for both the concave and convex banks. When strongly alined toward the concave bank the flow was least effectively influenced by measures intended to protect that bank.

VIII. COST OF STREAMBANK PROTECTION BY NATURAL MEANS

COSTS CITED IN REVIEWED LITERATURE

The reviewed literature provides almost no information on the dollar costs of natural streambank protection. That which is reported is quite out of date, as recent publications deal primarily with technical aspects of bank stabilization.

A few older costs for natural protection are available and may be of interest for comparative purposes. In one instance, in 1962, bids were received for provision of grass sod and heavy woven mats of jute yarn (supplied in rolls) to stabilize embankments, cut slopes, drainage channels and other elements of a project for a section of the Baltimore Beltway. The low bid price for the sod was \$0.45/square yard, installed, and that for the jute mats was \$0.40/square yard, installed. These figures did not include slope preparation (1). In another situation, a central Wyoming project that was constructed during 1953-61 included the planting of willow and Russian olive seedlings behind mechanical erosion control works (jacks, groins, and jetties) to stabilize streams. However, the reported costs were not separated so that those for planting could be identified (2).

---

[1]Anon., "Heavy Jute Mats Aid Erosion Control," Eng. News-Record, v. 169, n.1, July 5, 1962, 57-8.

[2]Miller, R. C. and W. M. Borland, "Stabilization of Fivemile and Muddy Creeks," Proc. ASCE, J. Hydraulics Div., v. 89, n.HY1, Jan. 1963, 67-98.

Costs for mechanical types of bank protection are also reported in the literature. These, too, are older costs, mainly from the early 1960's. Because they do not directly apply to natural methods for bank stabilization they are not presented here.

One article of interest did not provide actual costs but instead made an evaluation of the economics of river bank stabilization (1). The author analyzed the costs of bank protection compared with revenue that is lost from bank caving and the revenue that is restored by accretion of sediment adjacent to a river bank. The various bases that might be used to compare benefits and costs were discussed and a general procedure for economic analysis was suggested. This procedure includes:

(1) Determine the extent and cost of stabilization structures required to protect the actively caving bank and the annual charges appertaining thereto, using the most recent maps available for the reach under consideration.

(2) Planimeter and classify, as cropland, pasture, woodland, sand bar, and so on, all of the land on the floodway under consideration.

(3) Project probable bank lines as far into the future as possible, based on study of past maps, aerial photographs, and any other pertinent available data.

(4) Planimeter by classes the lands indicated for destruction. Compute the loss of revenue corresponding to the indicated loss of land

---

[1] Senour, C., "Economics of River Bank Stabilization," Proc. ASCE, J. Waterways and Harbors Div., v. 87, n. WW2, May 1961, 17-26.

and determine the cost of levee setbacks, adjustments of power lines, pipelines, bridges, railways, and highways required, the cost of moving other types of structures, and the value of non-removable structures that erosion will destroy.

(5) Discount revenue losses in (4) by estimated net revenues derived from accretions during the life of the project.

(6) For the reach under consideration, planimeter the area actually destroyed by bank recession during a past period of years equal to the time period being used in the projection study, available data permitting.

(7) Estimate collateral benefits deriving from stabilization of banks.

(8) Determine the ratio between tangible benefits (direct and collateral) and costs, "bolstering it if and as necessary, by such eloquence with regard to intangibles as conscience will permit."

CURRENT COSTS AND COST FACTORS

The costs involved in the use of a natural method for streambank stabilization by a riparian landowner are very difficult to establish. This is because the landowner may already have some or all of the needed equipment and needed materials at his disposal. Also, he and his family might provide all of the necessary labor to complete the project. In a limiting case, then, there could be very little cash outlay required to complete a project. At the other limit, the landowner might contract to have the entire project carried out. Then, the location of the site with respect to contractor, labor force, material sources,

material disposal, and equipment sources will be a determinant in the cost of streambank protection.

The cited variables and the lack of a specific streambank location for which to determine project costs make it preferable to treat costs on the basis of cost factors. This involves an evaluation of the work and material components of different types of natural stabilization methods. To do this, assumed hypothetical situations are used and the previously established separation of methods among the categories of bank shaping, vegetative management and riparian land management are followed.

COST FACTORS FOR BANK SHAPING

Typical Cases

Several typical situations exist where bank shaping is applicable. These include general bank and slope shaping, local bank and slope shaping, partial point bar removal by scalping above the water line, complete point bar removal, and placement of dredge spoils at banks.

General Bank and Slope Shaping

General bank and slope shaping involves reshaping and grading a river bank to an appropriately selected alinement and side slope. For evaluation, a hypothetical situation will be assumed: a side slope of 2H:1V or flatter might be selected for a typical river bend requiring stabilization over a distance of approximately 2000 feet and a height of 20 feet. This operation is similar to slope preparation preliminary to placing riprap in a Willamette River revetment.

Job components include: site staking; vegetation stripping from the work surface; vegetation disposal or storage for reuse; earth excavation, loading, hauling, and dumping at a disposal site; periodic site resurveying and restaking; and final grading of the shaped slope. Presumably this would be followed by some type of vegetative planting (discussed later). Earth excavation will usually involve activities both above and below the water level. The amount of earth to be removed will depend upon both the initial slope and the final slope involved. The amount of vegetation stripping to be done will depend upon the type of growth occurring at the bank. If a cutbank is involved, there will be little vegetative cover. Grass and other short vegetation need not be removed in advance of earth removal.

Each of the identified job components involves equipment and labor. For the hypothetical situation presented, a breakdown of these is estimated to be as follows:

Job Component	Equipment	Labor (Man-Days)
Surveying and staking	Surveying	3
Vegetation removal	Chain saw Tractor & attachments Loader Truck	4
Earth removal	Tractor & attachments Loader Dragline Truck	400
Final grading	Tractor & attachments	2

Local Bank and Slope Shaping

In contrast to general streambank shaping, local bank shaping concerns short reaches on the order of 100 feet or so in length. Local hard points or other bank irregularities that cause bank scour are reshaped in this type of an operation. Bank irregularities that set out from the general bank line would be removed and those involving setbacks from the general bank line would be filled. As local bank and slope shaping is a much smaller job than general bank and slope shaping, it follows that the costs are lower.

Job components are similar to those for general slope shaping except that earth and riprap fill could be involved rather than earth removal. For the hypothetical situation of a 20 foot irregularity along 100 feet of bank that is 20 to 30 feet high, the job components might be estimated as follows:

Job Component	Equipment	Labor (Man-Days)
Surveying and staking	Surveying	1
Vegetation removal	Chain saw Tractor & attachments Loader Truck	1
Earth removal or earth and riprap placement	Tractor & attachments Loader Dragline Truck	14
Final grading	Tractor & attachments	1

Point Bar Removal

Point bars on the inside of meander bends can be a critical cause of bank scour. Accordingly, their total removal or partial removal by scalping can relieve the shear stresses against the opposite bank. Point bar scalping is appropriate where the removal of the entire bar would not be necessary or would be restricted in some manner.

The following hypothetical conditions might be assumed for a typical point bar in the Willamette River: a length of 1000 feet, a width of 100 feet subject to removal, an average height above the low-water level of 3 feet, a vegetative cover including young willows and stranded logs, and an extension of the bar into the channel by 50 feet before the low-water depth reaches 3 feet. From the viewpoint of protecting the concave bank it would be desirable to place the removed gravel against the base of the concave bank. However, it is assumed here that the river width and depth prevent this from being done directly.

The job components that would be involved in partial point bar removal (not below the water level) include: vegetation and debris stripping, removal and disposal; gravel excavation, loading, hauling and dumping at a storage or use site; periodic site surveying and staking; and final grading to eliminate all depressions. An estimated breakdown of job equipment and labor for the hypothetical situation is:

Job Component	Equipment	Labor(Man-Days)
Surveying and staking	Surveying	1
Vegetation removal	Chain saw Tractor & attachments Loader Truck	4
Gravel removal	Loader Truck	150
Final grading	Grader	1

If complete point bar removal to a depth of 3 feet below the low water were instead planned, the job components would include use of a dragline at the water's edge to remove in-stream gravels and the berm that would probably be left during gravel removal below the stream level at the exposed bar. The new breakdown of job components would be:

Job Component	Equipment	Labor (Man-Days)
Surveying and staking	Surveying	2
Vegetation removal	Chain saw Tractor & attachments Loader Truck	4
Gravel removal to level of water	Loader Truck	150
Additional gravel removal to 3 feet below water level	Dragline Loader Truck Pump & lines	60
Final grading behind protective berm	Grader	1
Removal of berm	Dragline Loader Truck	10

Channel Dredging and Spoil Placement

Channel dredging, when allowed, can be quite beneficial in preventing erosion. Dredging can prevent bar growth and shoaling that forces stream flows toward the banks. Placement of dredge spoils in appropriate locations can protect erosion-prone banks by supporting the bank toe or overlying the bank.

The job components that would be involved in dredging operations include: site location; spoilbank location; movement of dredge to site; dredging and spoiling; periodic inspection after dredging is complete. No estimated breakdown of labor and equipment is made here because of the variable quantity of materials to be dredged.

Comparison

The costs of local and general bank shaping are mainly composed of initial expenditures. Point bar scalping or complete removal and dredging operations, however, require periodic repetition, as sediment deposition is usually a continuing process. The channel must be maintained in such a case.

COST FACTORS FOR VEGETATIVE MANAGEMENT

Vegetative management can be divided into three parts: removal of fallen trees and debris, initial plantings, and continuing maintenance. Management techniques vary with the size of streambank vegetation, which ranges from short grasses through shrubs, vines and bushes, to tall trees.

Vegetation Removal

The removal of fallen trees and debris from the channel, in addition to the removal of likely-to-fall trees on the banks, is of importance in any streambank management program. Elimination of channel debris relieves local scour by removing the sources of flow deflection, eddy formation, and bar formation. Trees whose fall is imminent can significantly weaken the bank.

Vegetation removal is the only major job component. Different types of equipment will be required, however, depending on the job. Cutting trees on the bank would only require a chain saw in most cases. Removal of channel debris, on the other hand, would often require the use of a dragline of some type. Depending on the extent of the operation, it can be estimated that vegetation removal would involve approximately 2 man-days with variable equipment and supplies.

Planting of Vegetation

The planting of vegetation normally requires some form of bank slope preparation. This may vary from local shaping with a shovel for individual plants to general bank shaping in preparation for a grassy or other continuous vegetal cover. The cost factors for the latter type of bank shaping have already been discussed. Where bank shaping and vegetative plantings are combined, the cost factors are normally additive.

Because there is so much variability in the extensiveness and type of streambank vegetation that may be planted, it is difficult to identify

the cost factors in detail. For simplicity, a hypothetical situation will be assumed where some form of continuous cover is to be planted on a sloped streambank (e.g., 2H:1V) for a bank about 20 feet high. A unit length of 100 feet along the bank will also be assumed.

Job components for vegetative plantings include: slope preparation; soil preparation; sod, seed or plant delivery and placement; watering and fertilizing; and replacement of vegetation in spots where the initial planting was unsuccessful. These job components involve both equipment and labor. The components vary with the type of vegetation being planted. An estimated breakdown of such components for grass, sod or bushes is as follows:

Job Component	Equipment	Labor (Man-Days)
Slope preparation	(see bank shaping)	(see bank shaping)
Soil preparation	Tractor & accessories Rakes Shovels Chemical spreaders	1
Planting & replanting	Tractor & wagon	6
Watering & fertilizing	Pump & line Fertilizer spreader	1 (periodically for several weeks)

Vegetation Maintenance

Maintenance of vegetative cover on a riverbank is very important. Shrubs must be pruned and vegetation in general requires mulching. When thick, heavy brush is scoured away, the exposed bare soil near the

remaining vegetation is attacked by secondary currents. Because of this, replanting and the maintenance of a fairly continuous cover are advised.

The same hypothetical situation as for planting of vegetation may be used to discuss job components in vegetation maintenance. The job components include: periodic inspection; mulching and fertilizer application; spraying for insect and disease control; pruning and trimming for length control; and replanting of injured and scoured vegetation. No estimated breakdown of equipment supplies and labor is made here, because of the unpredictable time requirements. However, as a collective maintenance package, it may be estimated that annual maintenance may involve 2 to 4 man-days and manually-carried tools and supplies.

Point Bar Vegetation

Point bar vegetation can be of prime importance in aggravating bank scour at high flows. Therefore, in many cases it is desirable to clear a point bar of vegetation in order to lower its profile.

This subject was dealt with in connection with point bar removal. For the hypothetical situation used, the job components, equipment and labor involved for removal of vegetation and large debris were given. If no gravel is extracted, the cut vegetation and debris could be stacked for burning at an appropriate time. The revised job needs would then be:

Job Component	Equipment	Labor (Man-Days)
Vegetation removal	Chain saw Tractor & attachments	2

COST FACTORS FOR RIPARIAN LAND MANAGEMENT

It is extremely difficult to quantify costs associated with methods of riparian land management because of the wide range of variables involved in different methods. Much of riparian land management involves decisions and alternative uses for near-bank lands. It is extremely difficult to associate costs of foregone agricultural production with an indefinite estimate of the reduced rate of bank erosion resulting from the applied riparian management technique.

A good vegetal buffer zone of 25 to 50 feet is helpful in providing a protective cover to retard surface runoff and gullying and in stabilizing the bank with a root matrix. Efficient and rapid bank drainage should be provided to avoid bank saturation. Control of irrigation water and its application is also important with regard to streambank saturation. The variables are simply too numerous for a proper generalized cost estimate to be made.

RELATIVE MAGNITUDES OF COSTS

The foregoing discussion may be summarized by means of a comparison of likely relative costs among the several techniques of natural streambank stabilization. These are for hypothetical general conditions, rather than for specific sites, as has already been pointed out.

Bank shaping activities are expected to involve the greatest amount of initial work and the greatest amount of specialized equipment. Shaping of the banks is not likely to involve much reshaping maintenance if the slopes are protected by vegetation and if shaping occurs in zones

where toe scour and bank undercutting are inconsequential. However, if bank undercutting does occur, maintenance of the shaped bank may be costly and frequent. Removal of gravel bars is also a costly technique, once the work extends below the water level. For complete point bar removal, both the initial work and the periodic repeating of this activity (at one- to four-year intervals, depending upon intervening winter runoff) must be done below the water surface. Re-scalping of point bars (at a similar frequency) can be done above the water level, so that this recurring cost is likely to be low. Both bar scalping and complete bar removal offer the possibility for recovering costs through the marketing of the sand and gravel that is removed. Channel dredging and spoil placement is another costly undertaking. In this case, it may be possible for the riparian owner to obtain the benefits of the activity without direct cost if a governmental unit is dredging as one of its authorized activities (e.g., for navigation improvements).

The relative magnitudes of costs for the above-described bank shaping activities are summarized in Table 2. Also shown is similar information for vegetative management and riparian land management.

Vegetation management techniques all generally include low-cost activities. Only the extensive planting of new vegetation and vegetative fences is likely to represent sizeable costs, comparable to those for the moderate-cost bank shaping activities.

Riparian land management is concerned, in part, with optional ways of using land and involves many intangible costs. Generally, top-of-bank management is low-cost. Where fencing to control access or ditching

TABLE 2. RELATIVE COSTS FOR NATURAL STREAMBANK PROTECTION

Type of Activity	Relative Magnitude of Initial Costs	Recurring Costs	
		Relative Magnitude	Frequency
<u>Bank Shaping</u>:			
General bank and slope shaping	high	low [a]	infreq.
Local bank and slope shaping	moderate	low [a]	infreq.
Complete point bar removal	high [b]	high [b]	1 - 4 years
Point bar scalping	moderate [b]	low [b]	1 - 4 years
Channel dredging and spoil placement	high [c]	high [c]	1 - 4 years
<u>Vegetative Management</u>:			
Removal of endangered and fallen vegetation and debris	low	low	annually
Vegetation planting	moderate [d]	low	annually
Maintenance of existing vegetation	low	low	annually
Point bar vegetation and debris control	low	low	annually
<u>Riparian Land Management</u>:			
Top-of-bank-vegetation zone	low	low	infreq.
Controlled access	moderate	low	annually
Irrigation control	none	none	none
Drainage control	moderate	low	

[a] Assuming that some form of vegetal protection is used.

[b] Complete cost recovery may be possible through sale of removed gravel.

[c] Possibility that costs might be borne by governmental unit as authorized activity.

[d] Assuming that any large-scale bank shaping is considered separately.

and tile installation to control drainage are involved, initial costs are greater and perhaps are of similar magnitude to the planting of new vegetation or to local bank shaping.

IX. NATURAL MEANS OF STREAMBANK STABILIZATION APPLICABLE IN THE WILLAMETTE RIVER BASIN

This chapter presents the streambank stabilization procedures applicable to the Willamette River and its principal tributaries that involve natural means such as bank shaping, vegetative management, and riparian land management. It is believed that this might conceivably be done within a landowner's own resources. The potential applicability of such methods was identified and discussed in Chapter VI, based upon available literature about stabilization elsewhere (Chapters II and III), pertinent river features in the Willamette Basin (Chapter IV), and investigation of particular river sites (Chapter V). Because of the impracticability of field-testing several potentially usable techniques in a short period of time and with limited resources, model studies were instead carried out to test methods at reduced scale under simplified conditions. The qualitative findings (Chapter VII) provided a technical evaluation of the techniques to determine more about their applicability and effectiveness. A cost evaluation of the potentially usable techniques was also made (Chapter VIII). From the foregoing, the applicable natural techniques are presented in this chapter, together with assessment of their relative effectiveness in controlling streambank erosion.

GENERAL FEASIBILITY AND EFFECTIVENESS

One of the most critical problems to deal with in streambank stabilization along the Willamette River and its largest tributaries is the erosiveness of the streamflow at concave banks of sharp curves. There and at other locations where abrupt changes of flow alinement occur, the flow crowds the banks, producing high velocities and exerting strong shear stresses against the banks. The toes of such banks are particularly exposed to the scouring and undercutting action of the flow.

To cope with these critical problem reaches of the large rivers, natural means of streambank stabilization are not effective. Even their retarding influence over the erosion process is not likely to be great. The overpowering ability of the Willamette River and its larger tributaries to meander involves sufficiently large forces exerted against the concave banks that only massive and extensive mechanical methods of bank stabilization can adequately halt the advance of the river and provide permanent protection.

There are many other zones away from such locations where streambank erosion also occurs. At these, the river forces are not of the same severity and therefore possibilities do exist for the application of natural means of bank protection. These means vary in their effectiveness with the river circumstances encountered. In some situations, they can be expected to arrest erosion for long periods of years; in others, they can only be expected to retard the rate of erosion.

The timeliness of application of the method is critical. A bank may be stable for many years and then suddenly begin to erode due

to a new or aggravated cause. If the erosive mechanism only gradually develops, timely use of a natural method or limited mechanical method of bank protection will retard the growth of this erosive action and may even provide stability for a relatively long time. If timely action is not taken, the extent of scour will progress to the point where alinement and other flow conditions are greatly worsened so that remedial work is much more difficult. The Willamette River situation near the Corvallis Water Treatment Plant illustrates the severe erosion problems where timely action was not taken.

Streambank erosion is a problem that extends beyond property lines. The eroded zone itself may extend along the banks of two or more riparian property owners. Often, erosion at one place along the bank is the result of flow mechanisms that are triggered upstream or across the stream, at property of a different riparian landowner. Consequently, attempts to alleviate and prevent streambank erosion may often require the joint efforts of groups of riparian landowners. Timely action is usually difficult when more than one riparian landowner is involved.

APPLICABLE TECHNIQUES

In addition to the river circumstances encountered, the technique of natural bank protection that is selected from among those that are applicable will also influence the effectiveness of erosion control. Among the three broader categories--bank shaping, vegetative management and riparian land management--are several individual techniques that vary in their applicability and effectiveness. Table 3 describes these

TABLE 3. TECHNIQUES FOR NATURAL STREAMBANK STABILIZATION WILLAMETTE RIVER AND TRIBUTARIES

Technique	Objectives	Locations of Applicability	Special Considerations	General Procedures
BANK SHAPING TECHNIQUES:				
Removal of local bank irregularities.	Remove false points, constrictions, bank depressions and other irregularities (setouts/setbacks). Eliminate local flow deflections, flow constrictions, and eddy generation. Develop smooth, well alined flow. Eliminate local scour. Reshape bank locally to make compatible with adjacent banks.	Straight banks Concave banks	Extent of erosion now caused. Is change beneficial or detrimental? Local flow and channel alinements. Characteristics of soil that will be exposed to flow. Availability of suitable fill material. Effects of making changes only above the low-water level. Protection of reshaped bank surface. Protection of water quality during work.	Determine need for reshaping. Determine extent of reshaping. Obtain permit. Work during summer low flows. Remove projecting irregularity, disposing of spoils out of stream. Place suitable fill material where needed. Final grading of slope. Protect reshaped bank with compatible vegetation, providing temporary protection during growth period.
Bank slope flattening. Waterway widening	Flatten bank slopes to reduce local velocities and shear stresses. Widen waterway for large discharges. Provide better slope to establish vegetal growth.	Straight banks Concave banks	Extent of present erosion. Extent of beneficial reshaping. General flow and channel alinements. Characteristics of soil that will be exposed to flow. Smooth transitions between reshaped bank and adjacent banks. Sediment transport and bar formation. Potential for bank toe scour. Protection of water quality during work.	Determine need for reshaping. Determine extent of reshaping. Obtain permit. Work during summer low flows. Remove vegetal cover as needed. Remove bank material, disposing of spoils out of stream. Final grading of slope. Protect flattened bank with compatible vegetation, providing temporary protection during growth period.

TABLE 3, continued

Technique	Objectives	Locations of Applicability	Special Consideration	General Procedures
Point bar removal	Increase waterway to reduce velocities and shear stresses against concave bank. Realine flow away from concave bank. Reduce sharpness of curve and strength of secondary currents.	Channel bends In stream	Sharpness of bend. Extent of present erosion. Upstream and general flow alinement. Extent of removal and of benefit to be obtained. Location of strong secondary currents. Sediment transport and bar rebuilding. Scalping vs. total removal. In-stream removal. Bar ownership. Fishery constraints. Frequency of repeating bar removals. Protection of water quality during work.	Determine extent of removal, whether scalping or complete. Determine extent of in-channel removal. Obtain permit. Work during summer low flows. Use turbidity control measures. Clear off vegetation and debris. Remove bar material. Final grading of bar surface.
Dredge spoil placement Channel dredging	Protect erosion-prone banks with thick sloped layer of gravel. Support base of banks against caving. Prevent bar growth and shoaling that forces flow towards banks. Prevent closure of channel branch and greater flow through remaining channel.	Straight channels and banks Curved channels and banks In stream	Locations of present bank scour, undercutting and caving. Overall benefits and detriments to channel. Flow and channel alinements. Shape of placed spoils. Effects on sediment transport and streambed equilibrium. Navigation and fishery constraints. Frequency of repeating dredging. Protection of water quality during work.	Determine extent of erosion (actual/potential). Determine locations needing dredging and banks to benefit from spoil placement. Form or work with local improvement group to prepare information and arguments. Seek state and federal agency support for project. Request to District Engineer, Portland District, Corps of Engineers, for dredging.

TABLE 3, continued

Technique	Objectives	Locations of Applicability	Special Considerations	General Procedures
Local drainage alinement	Minimize flow deflections and eddy formation due to inflow of local drainage. Minimize projections of protective material into river.	Straight banks Concave banks	Extent of present erosion. Relative discharges in both streams. Local flow and channel alinements for both streams. Angle of entry of local inflow. Projection of culverts and other man-made features. Local scour protection.	Determine extent of flow deflection, eddy formation, and local scour. Determine needed alinement for inflow. Rebuild or reshape outfall to give proper alinement. Rebuild erosion protection to eliminate projection into river. Repair local scour damage.
Slope flattening above lower-bank revetment	Protect sharp curves from erosion. Reduce cost of massive revetment. Combine massive protection with natural protection. Extend use of natural technique into zone of more adverse flow conditions.	Concave banks	Extent of present erosion. Severity of toe scour. Extent of beneficial reshaping. General flow and channel alinements. Bend curvature. Soil characteristics of bank. Smooth transition with unreshaped banks.	Determine necessity for protection. Determine extent of protection needed. Obtain permit. Work during summer low flows. Use turbidity control measures. Remove vegetal cover as needed. Remove bank material, disposing of spoils out of stream. Shape lower bank. Excavate toe trench. Place filter/bedding material against lower bank. Place adequate-sized riprap in revetment zone. Shape and grade upper bank. Protect upper bank with compatible vegetation.

TABLE 3, continued

Technique	Objectives	Locations of Applicability	Special Considerations	General Procedures
Complete channel realinement	Form new concave bank in better future alinement. Reduce bend curvature and abrupt alinement changes. Provide a smooth gradual curve.	Concave banks	Severity of present and potential erosion. General flow and channel alinements over extended reach. *Probability of channel shift to anticipated alinement.* Soil characteristics in concave bank, vertically and aerially. Estimated land time for work. Early loss of land use. Protection of realined and reshaped bank. Protection against toe scour.	Analysis of likely bank loss and future configuration of which bank shaping might be effective. Proper design of future bank. Excavation of future bank behind berm. Final shaping of future bank. Toe protection of future bank. Slope protection of future bank.
VEGETATIVE MANAGEMENT TECHNIQUES:				
Removal of fallen trees and debris	Remove sources of flow deflection, eddy formation, and bar formation. Relieve local scour.	Straight banks Concave banks In stream	Extent of existing and potential erosion. Is removal beneficial or detrimental? Local flow alinement. Disturbance of streambed or bank. Gravel bars. Possible use to protect base of top of bank or to close floodway.	Determine necessity for removal. Determine disposal site. Obtain permit. Work at time of suitable water depth for attachment and movement to disposal area. Repair any bank damage.
Removal of likely-to-fall trees	Remove potential cause of bank weakening.	Straight banks Concave banks Top of bank	Proximity to top of bank. Wind exposure of tree. Exposure of roots. Size and weight of tree. Bank saturation conditions. Use of felled tree as debris barrier.	Determine necessity for removal. Determine safe felling direction. Fell and remove tree to disposal site.

TABLE 3, continued

Technique	Objectives	Locations of Applicability	Special Considerations	General Procedures
Vegetation removal from bars	Increase waterway for moderate and large flows. Reduce velocity and shear stress at nearby banks. Relieve local scour.	In stream Convex banks	Extent of erosion. Benefits and detriments of removal. Wildlife habitat. Method of disposal. Adverse effects of leaving cut vegetation on bar. Periodic repetition.	Determine necessity for removal. Determine disposal method or site. Obtain permit. Cut vegetation. Dispose of vegetation.
Planting of dense short vegetation Planting of dense bushy vegetation	Reduce bank erosion. Develop a root matrix to hold the soil. Develop a buffer zone above the soil to reduce velocities and shear stresses.	Straight banks Concave banks Top of bank	Bend curvature. Severity of flow attack. Bank slope. Continuous cover. Uniformity of vegetation size. Proximity of long vegetation. Maintenance during growth establishment. Type of vegetation.	Determine extent of zone needing protection. Prepare slope and soil. Plant suitable vegetation. Fertilize and water until growth is well established. Replace unsuccessful plantings.
Replanting of scoured zones	Reduce bank erosion by replacing vegetation that has been scoured.	Straight banks Concave banks Top of bank	Cause of scour. Need for additional bank shaping. Compatibility with surrounding vegetation. Maintenance during growth establishment.	Determine need for replanting. Prepare slope and soil. Plant vegetation. Care for vegetation until well established.

TABLE 3, continued

Technique	Objectives	Locations of Applicability	Special Considerations	General Procedures
Vegetation growth control	Prevent flow deflection and eddy formation caused by protruding vegetation	Straight banks Concave banks	Periodic inspection. Accessibility.	Determine need for trimming. Cut vegetation that protrudes or is too long. Place cuttings at ground level for added protection.
Planting at foreground of cutbanks	Establish vegetal protection in caved-off soil at base of cutbanks. Prevent bank scour.	Straight banks Concave banks	Bend curvature. High-water flow relief at opposite bank. Availability of caved-off soil. Accessibility. Prompt action.	Determine likelihood of success based on hydraulic conditions and soil availability. Plant tree cuttings (willows) and fast growing grasses.
Plant living fences	Provide barrier to debris and retardant to overbank flood flows. Blockage of little-used flood channels and highwater chutes to prevent future cutoffs.	Low convex banks Tops of all low banks	Ground elevations. Existing trees. Available debris and cuttings.	Determine appropriate locations. Plant trees closely in two or more rows. Place available debris between all trees, planted or existing. Care for planted trees until well established.
Tree buffers and deflectors	Provide buffer zone of trees and accumulated debris along a bank to reduce erosion. Deflect flows from a bank to reduce erosion.	Straight banks Gradual concave banks In stream	Bend curvature. Near-bank velocities. Risks and hazards of being swept away. Available trees and debris.	Determine if location is suitable for such vegetal structures. Obtain necessary number and size of trees. Cable together securely. Anchor securely to bank. Add available debris between trees and bank so as not to be swept away. Plant vegetation on the slope being protected.

TABLE 3, continued

Technique	Objectives	Locations of Applicability	Special Considerations	General Procedures
RIPARIAN LAND MANAGEMENT:				
Top-of-bank vegetation zone	Prevent soil erosion by providing cover to retard surface runoff and gullying by encouraging infiltration. Provide buffer zone between erosion-susceptible bank and top-of-bank activities. Provide a root matrix to hold the soil together.	Top of bank	Rate of bank erosion. Cause of bank erosion. Top of bank land use.	Determine rate of bank erosion. Maintain a vegetation buffer zone of reasonable width to protect bank vegetation and keep disturbing activities away from the bank.
Controlled irrigation water application	Avoid saturation of bank and seepage forces that could cause bank caving. Maintain health bank vegetation.	Top of bank	Soil characteristics at bank. Water for vegetative protection. Land cultivation practices.	Determine current irrigation application practices. Modify practices as needed to control soil moisture.
Provision of bank drainage	Provide efficient, rapid drainage of excess water to avoid bank saturation.	Top of bank	Bank soil characteristics. Water table fluctuations. Ease of installation.	Determine ability of soil to be rapidly drained. Determine ease of installation drain pipes and tiles. Excavate ditches and install drains. Drive pipes from face of bank. Repair all soil damage at exposed areas.

TABLE 3, continued

Technique	Objectives	Locations of Applicability	Special Considerations	General Procedures
Control over bank access and traffic	Avoid trail formation, concentrated runoff, and local erosion. Protect soil and vegetal cover.	Concave banks Top of bank	Nature of vegetal buffer. Steepness of bank.	Determine zones to be protected. Provide vegetative fencing where possible. Install wire fencing elsewhere. Maintain periodically.
Hydraulic design of river-related structures	Prevent bank and channel disturbances due to construction and presence of river-related structures.	Straight banks Concave banks In stream	Nature of structure. Types of disturbances. Irrigation intakes. Boat docks.	Determine adverse bank effects of structure. Anticipate these through design. Construction methods to minimize adverse bank effects.

techniques, their objectives, their locations of application, special considerations in use of the technique, and the broad procedures involved. The accompanying discussion elaborates on these techniques and treats their relative effectiveness and costs.

Bank Shaping Techniques

Bank shaping techniques can be used to prevent some types of local erosion, to retard other local erosion and to even retard more extensive erosion. The techniques will not completely prevent the more extensive forms of erosion, however. The effectiveness of bank shaping techniques is enhanced by the conjunctive use of vegetative protection and riparian land management.

Some bank shaping techniques, such as removal of bank irregularities, offer effective means at moderate cost to cope with problems of local scour. Similarly, scalping or complete removal of point bars offers an economical method (due to marketability of the gravel) of relieving stresses against some concave banks if the upstream flow alinement is favorable, although this technique must be repeated periodically. Slope flattening (with corresponding channel widening) will be effective in straight reaches to reduce velocities and allow vegetal growth that gives added protection. However, slope flattening on concave bends, which is very beneficial in relieving bank shear stresses, is more costly and not of long term effectiveness unless accompanied by point bar removal, since the erosion and related undercutting of the concave bank will allow the channel to shift and cause the flattened concave bank to eventually be eroded into a steeper slope again. Channel dredging and

gravel disposal against eroding banks offer the cheapest and most effective short term technique of bank shaping, if it is done at federal expense for navigation rather than at riparian landowner expense, and offer both a protective layer against erosive forces and a larger flow channel away from the bank. However, this technique must be repeated periodically for effectiveness. On a smaller scale, low-cost bank and outfall shaping to provide a better alined entry of local drainage to the river and to prevent projection of local riprap into the flow will do much to eliminate flow deflections and eddy formation that lead to local scour. At sharp curves, bank shaping to flatten and vegetate the upper portion of a concave bank can be effectively combined with the necessary massive revetting of the toe and lower bank to provide long-term protection at less cost than for a full revetment. Finally, bank shaping might be applied to the formation of an entirely new future concave bank in order to anticipate erosion of a sharp bend and prepare to completely realine the river into a gradual curve. While the resulting combination of a smooth gradual curvature and a flat concave bank favor bank stability, the technique is costly and there would still remain concern for the security of the toe of that bank--so that massive toe protection would also be recommended.

Vegetative Management Techniques

In-stream, adjacent-to-the-bank vegetation and debris management to remove fallen trees, snags and other large stranded vegetation is effective and inexpensive in relieving local scour caused by deflected flows and eddies. Similarly, removal of fallen trees from the bank

provides the same relief. Removal of likely-to-fall trees from the face or the top of the streambank will inexpensively help avoid conditions that might aggravate erosion. Removal of vegetation from bars can be economically effective in relieving local scour. All of the foregoing techniques must be repeated periodically.

Planting and maintenance of dense grassy vegetation will effectively resist scour on flat-sloped banks as long as toe protection is provided by some other means and no sources of localized scour are present. Uniform-sized, dense, bushy vegetation provides even better protection under similar circumstances. Greater costs are generally involved in slope preparation than in vegetal plantings but for banks not subject to severe flow conditions the benefits will justify the costs involved. At sharp bends of the larger rivers these techniques will involve frequent maintenance. Control over the growth and size of vegetation offers an inexpensive, effective technique for preventing and eliminating local scour at nearby banks caused by flow deflection and eddies from protruding larger vegetation. Planting of vegetation on caved-off soil at the base of high banks will inexpensively help to retard erosion there.

Suitable vegetation for streambank protection in the Willamette Basin includes herbaceous material such as tall fescue, creeping red fescue, rye grass, canary grass, brome grass, bentgrass, birdsfoot trefoil and meadow foxtail, groundcovers and shrubs such as blackberry, salal, dwarf willows, dogwoods, rose, hazel and vine maple, and trees such as several types of willows, black cottonwood, maples, alders, Oregon ash and black hawthorn. Specific use depends upon local soil conditions.

Vegetative plantings to create living fences are less expensive than timber structures for blocking off little-used flood channels and to provide debris barriers and retard overland flow. Trees cabled together and anchored to the bank can be used as a technique to retard or deflect the flow at the bank. However, their effectiveness is limited for the Willamette, where strong currents will damage the tree structure.

Techniques that incorporate vegetation with massive and extensive structures such as stone toe revetments, timber piles, and steel jacks are likely to be both effective and costly. A cost analysis for a particular site is likely to show sufficiently large costs so that a complete stone revetment may be a viable alternative, particularly since it offers greater confidence of permanence.

Riparian Land Management Techniques

Some riparian land management techniques appear to be primarily effective in preventing certain conditions that aggravate streambank erosion without increasing the stability of an existing bank. Other techniques can also help reduce the rate of erosion.

Provision of a top-of-the-bank vegetation zone to protect the soil from erosion is a relatively low-cost and effective technique to retard surface runoff and gullying at the face of the bank. Controlled irrigation water application near the bank is essentially a costless technique and will aid in maintaining a low water table and minimal seepage from the face of the bank so as not to aggravate bank caving. The provision of a bank drainage system is a more costly technique with an unproven potential for reducing bank caving. Control over bank access and bank

traffic is less costly and is a useful preventative technique at concave banks to avoid trail formation and the concentration of runoff on the face of the bank. Proper hydraulic design and construction of river-related structures is a relatively costless technique for avoiding streambank damage or erosion-aggravating conditions. For the riparian landowner, this technique would principally relate to irrigation water intakes and boat dock facilities.

X. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Streambank stabilization by natural means along the Willamette River and its principal tributaries is feasible. However, most of the applicable techniques will not completely halt streambank erosion. Most of the applicable techniques will, however, retard erosion; but for some techniques the decrease in erosion rate will be almost imperceptible. The success of streambank stabilization by natural means ultimately depends upon the location of the streambank being protected with respect to the river flow alinement. In some situations almost every natural technique for stabilization will be effective but there will not be any serious erosion problem. In other situations, the erosion problem will be so severe that no combination of natural methods will halt erosion and the reduction of the erosion rate by these means will only be possible by frequent re-use of the techniques.

The critical problem is one of highly concentrated flows and strong secondary currents at sharp curves and other points of abrupt change in flow alinement. This condition makes the adjacent concave banks extremely vulnerable to erosion. Such erosion is particularly severe at the toe of the bank, beneath the summer low-water level where no natural method of bank protection can be applied to give permanent protection. Dredge spoils can be placed there but will only provide temporary seasonal

protection; bank shaping can be done below the water surface but toe erosion will negate its beneficial effects over one winter season; tree buffers and deflectors will not last in the swift currents for very long; protective vegetation will not withstand permanent inundation; and other natural techniques have even less applicability. Scour at the toe of a streambank will lead to the bank's undercutting and collapse. In such critical zones, only massive structural methods of bank protection, such as stone revetments, can provide adequate toe protection and permanent bank stabilization. Natural techniques will only alleviate erosion, not halt it; and the degree of alleviation for the more-effective techniques will depend upon the frequency of re-application of the technique.

At many locations away from sharp changes in flow alinement and locally concentrated flows, streambank stabilization can be achieved by natural means to halt or retard bank erosion. This protection can even be expected to last for periods of up to several years. These locations are found along straight reaches, at the convex banks of river bends, and even at some concave banks of very flat curves (relative bend curvatures of perhaps 10 or 12). The types of bank earth materials encountered will be one of the most important influences. Wherever the older strata (such as the Linn Gravels, the Diamond Hill clayey soils, or the Willamette Silts) are exposed, natural techniques will have a better basis for success than where more-recently deposited soils are encountered, due to the greater resistence to erosion of these older strata. Their slower erosion provides more time for vegetal root structures to become well-established if bank shaping and planting are undertaken.

The applicable natural techniques of bank protection are shown in Table 4. Collectively, they are more suitable for some situations than others. Individually, this is even more the case. Thus, several techniques may be used at concave banks (the most severe test of bank protection) but they are all either relative ineffectual or, where effective, of relatively short duration unless repeated frequently. Several techniques may be used at convex banks, where they are not really needed to protect the convex bank. Instead, they help enhance the protective measures applied to the concave bank. They are generally of short duration and require frequent repeating. Several techniques may be used along straight reaches where they will be quite effective and long lasting. Several techniques may be applied within the stream to enhance the stability of nearby banks. Almost all of these are of short duration and require frequent repetition to maintain their effectiveness. Finally, there are several techniques that may be applied to a zone along the top of the bank. Some are effective there and others are mainly intended to prevent conditions from developing that would aggravate bank erosion.

Thus, natural methods of bank stabilization have a limited role in the Willamette for halting erosion. They serve primarily to halt it in straight reaches and to reduce its rate in some curved reaches where the flow alinement changes only gradually. The main constraint upon broader applicability of natural techniques is the inability to protect the toe of the bank. The placing of dredge spoils at the bank is one method that provides this protection, but normally only over one or two flood seasons at best. However, the possibility of combining a massive

TABLE 4. SUMMARY OF APPLICABLE SITUATIONS FOR NATURAL STREAMBANK STABILIZATION TECHNIQUES

Type of Method	Technique and Applicable Location				
	Straight Bank	Concave Bank	Convex Bank	In Stream	Top of Bank
Bank Shaping	Remove false points and other bank setouts. Remove constrictions. Fill bank setbacks. Flatten bank slopes. Widen waterway. Channel dredging and spoil placement. Local drainage alinement.	Remove false points and other bank setouts. Fill bank setbacks. Flatten bank slopes. Widen waterway. Point bar removal. Channel dredging and spoil placement. Local drainage alinement. Slope flattening above lower-bank revetment. Complete channel realinement.	Widen waterway. Point bar removal. Channel dredging.	Point bar removal. Channel dredging and spoil placement.	
Vegetative Management	Fallen tree and debris removal. Tree felling. Plant short vegetation. Plant bushy vegetation. Replant scoured zones. Vegetal growth control. Plant foreground at cutbank. Tree buffers/deflectors.	Fallen tree and debris removal. Tree felling. Plant short vegetation. Plant bushy vegetation. Replant scoured zones. Vegetal growth control. Plant foreground at cutbank. Tree buffers/deflectors.	Bar vegetation removal. Living fences.	Fallen tree and debris removal. Bar vegetation removal. Tree buffers/deflectors.	Tree felling. Plant short vegetation. Plant bushy vegetation. Replant scoured zones. Living fences.
Riparian Land Management	Hydraulic design of structures.	Control access. Hydraulic design of structures.		Hydraulic design of structures.	Vegetation zone. Controlled irrigation. Bank drainage. Control access.

revetment below the low-water level with natural techniques higher on the bank can provide a compromise solution--less expensive than a total massive revetment but not the same assurance of permanent protection.

RECOMMENDATIONS

With all forms of streambank protection, the timeliness of action is important. Erosion can be dealt with more effectively and less expensively if this is done at an early date, before flow alinements are greatly changed. This is most critical if natural means of protection are contemplated. Therefore, early recognition of the problem is essential and concerted action by more than one riparian owner is likely to be needed.

To allow early recognition of erosion problems, it is recommended that an erosion potential document be developed and, thereafter, routinely updated. This would serve the U. S. Army Corps of Engineers in their streambank management program as well as being valuable in dealing with programs of others and the review of permit applications. This document would consist of two elements: (1) the classification of erosion conditions and potential erosion conditions along the length of the Willamette River and its principal tributaries; and (2) the identification of causes (current or potential) at each location. All banks would be identified in a classification system with classes such as stable, potential erosion, slow erosion and rapid erosion. This assessment would be based upon the study of all U. S. Army Corps of Engineers aerial photographs since the photo-flight made just before the December 1964 flood. The information would be shown directly on the most recent aerial mosaics. The study of

aerial photographs would be supported by boat surveys along the full length of the streams to identify bank soil types and vegetation conditions and to determine the nature of bar and shoal conditions not evident from aerial photographs. This type of approach was followed to a limited extent only for the present study, focusing on particular identified problem areas.

Except along the Long Tom River, natural means of streambank stabilization are not known to have been applied on the larger rivers of the Willamette Basin. The techniques presented in this report should be attempted on tributaries of the Willamette at an early date, through the joint participation of the U. S. Army Corps of Engineers, affected riparian landowners and other governmental entities having interests or concerns relative to streambank protection. The Marys River from Philomath downstream might be one appropriate river for this due to existing problems and concerned citizens. The South Santiam River is another where problems exist and citizen organizations can facilitate action to control erosion. The Long Tom River also is in need of bank protection activities in several reaches. Because of the long-standing involvement of the Corps of Engineers there, this river should perhaps receive earlier attention.

The development of an extension-type pamphlet for public distribution has been proposed by Corps of Engineers personnel and mentioned in the contract document for the present study. The study conclusions are that only mixed success can be expected with natural means of streambank stabilization and that location along the river with respect to local

flow alinement is a critical determinant of the likelihood for stabilization success. It will be a difficult task to develop a self-explanatory general pamphlet to cover the broad range of conditions encountered from the main-stem Willamette down to moderate-sized tributaries on which Corps of Engineers reservoir projects retain technical feasibility. Riparian landowners will need specific additional information on river hydraulic conditions, streambank soils and vegetation, and ownership and rights questions that vary from location to location and cannot be adequately addressed in a general report or pamphlet. These landowners will need to consult with personnel from the U. S. Army Corps of Engineers, Oregon Division of State Lands, Oregon Department of Fish and Wildlife, Oregon Department of Water Resources, County Extension Agent, Oregon State University School of Agriculture, and others. Therefore, consideration should be given to the formation of a team that could be called upon for such assistance. One approach would be to use the pamphlet in conjunction with local public information meetings. This approach could be tried first for the Long Tom, Marys, or South Santiam River.

The Willamette River and some of its principal tributaries have their flows regulated by upstream reservoirs. The resulting river hydrographs differ from natural hydrographs because of the manner of reservoir operation followed to reduce flood peaks, evacuate stored flood waters at rates that do not exceed general bankfull levels, store spring runoff for summer uses, augment the small natural summer discharges, and evacuate the reservoirs again by late fall for winter flood control. Such activities alter flow durations and rates of change of stage and discharge. Consequently,

it is recommended that information about this influence upon streambank erosion and stability be sought. For example, investigation of a particular river reach might reveal that the top-of-bank vegetation is not as likely to be inundated but that vegetation on the face of the bank might be more often submerged due to particular reservoir operations. The characteristics of vegetation growing there could then be related to season and length of time of inundation to determine beneficial or detrimental aspects of flow regulation as regards natural bank protection. Similarly, the rates of change of flow under regulated conditions could be compared with natural rates of change and related to the extent and frequency of bank caving in order to determine the beneficial or detrimental features of various rates of change for particular bank materials and vegetative covers.

The rates of change of river water level affect the hydraulic gradients and seepage forces at streambanks. Where the river level is controlled through upstream reservoir regulation, beneficial or detrimental conditions pertaining to bank stability can be manipulated. The influence of flow regulation upon bank saturation conditions, seepage and stability merit investigation.

END

FILMED

3-85

DTIC